Astro-101

Black Holes

Content:

Introduction To Black Holes

1 Introduction

Welcome to Astro-101. My name is Sharon Morsink, and I will be your professor. With me are Jeanette Gladstone, Ross Lockwood, and Curtis Brown who will be your guides throughout our voyage to a black hole.

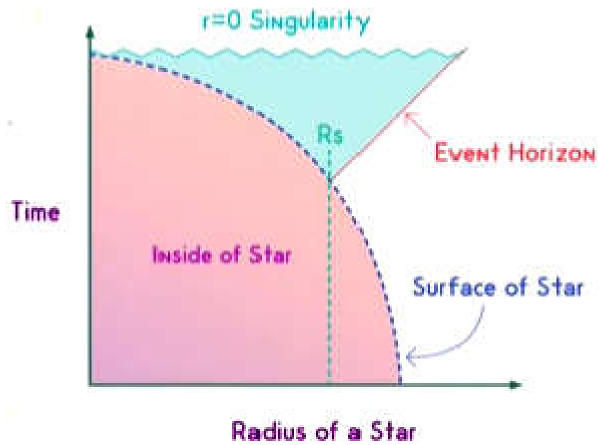


Illustration 1 : A collapsing star that forms a black hole

I did my research on the insights of black holes when I worked on my Ph.D. in theoretical physics. Over the years, I have also studied gravitational radiation and X-ray emission from black holes and neutron stars, which are dense, compact objects.

Illustration 2 : Force of gravity

The force of gravity fascinates me. How does gravity strength depend on an object's mass and size? How does gravity cause light to travel on curved paths?

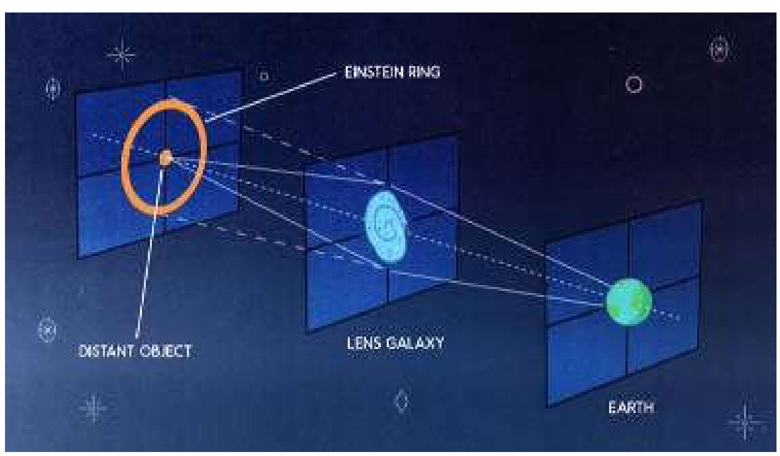
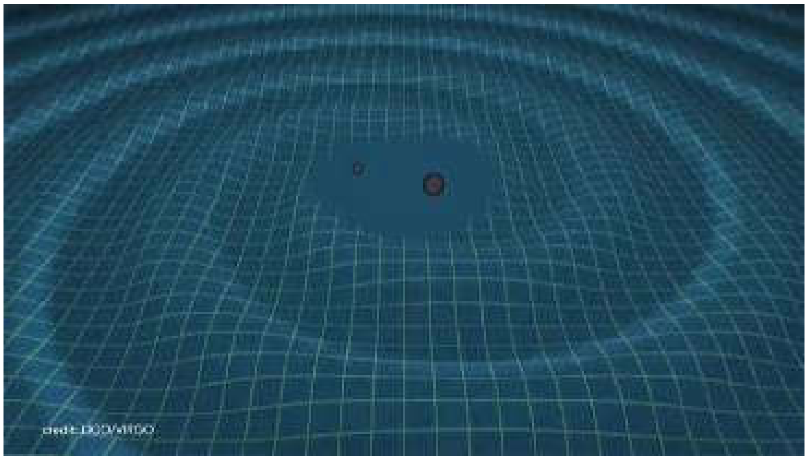


Illustration 3 : Gravitational lensing

Can we use the effects of gravity to observe black holes through gravitational lensing?



What exactly are the gravitational waves about scientists are so excited?

Hi there, I am Curtis. Some things you ought to know about me, when I am not on my side hustle slinging plywood, I am learning about black holes and studying engineering. I have been keen on learning about astrophysics since the very first time I watched my favorite science person, Neil deGrasse Tyson. In my spare time, I make pipe cleaner mustaches, and sit above the streets of Toronto in my palace of textbooks. My interest in black holes started in my undergraduate courses in astrophysics. We learned that black holes are the endpoint of stellar evolution for high-mass stars. What I am curious to learn is how the mass of a star can create a gravitationally collapsed object, a black hole. I know it has something to do with the 4D-structure of space-time, but the thing that I am interested in, is learning why massive black holes are much safer for astronauts and spaceships to visit than very small black holes. I cannot wait to get started. I will see you in the stellar nursery.

Hi, I am Ross. I earned a Ph.D. in condensed matter physics, relating to quantum mechanics. As a result, I am interested in the theories about microscopic black holes, and the effects caused by quantum mechanics like Hawking-radiation. I am excited about learning what happens inside of a black hole, what would happen to an astronaut and their equipment if they cross the event horizon, and what you would see if you look towards a black hole singularity. What would happen to an astronaut, and the information they were collecting, if they cross into a black hole, and what about the possibility of them escaping from the black hole. However, I am most excited to be one of your teachers throughout the course. I will see you in a little bit, when we begin talking about Newtonian gravity.

Hi there, my name is Jeanette Gladstone, and I am looking forward to help you learn more about black holes while sharing some of my sci-fi favorites. I also have a Ph.D., but mine is in black holes, or rather, in observing them. Yes, I spent three years of my life in the UK testing theories and ideas that had been put forward to explain a strangely bright class of black holes. I know that sounds a bit of an oxymoron, but it is true. At the end of those three years, I got to call myself Dr. Jeanette, and then moved across the pond to continue researching black holes here at the University of Alberta. My background means that my favorite sections lie towards the end of the course. Therefore, I am hoping you will stick around to the end to find out how it is actually possible to look at and study black holes. I hope to help you find the answers to questions such as how astronomers look at a black holes, how do they study them, and what do they look like, and more. Thank you for coming on this journey with us through space and time, and I look forward to chatting with you again soon.

In this course, we will be exploring these questions using animations, demonstrations, interactive learning objects, food analogies, calculations, readings, discussions, and other activities. In order to learn about black holes, we should first look at how black holes are portrayed in popular culture.

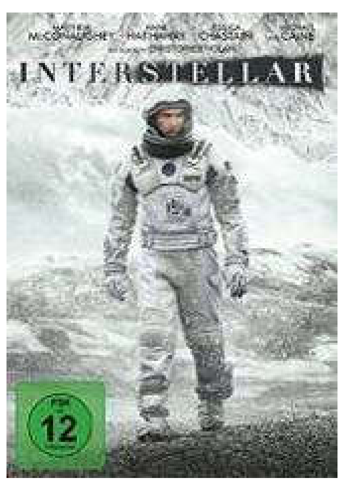
2 Black Holes In Pop Culture

Let us start our journey into the realm of pop culture with a franchise that has been attracting fans for the last 50 years. A generation of Star Trek enthusiasts grew up watching 'Star Trek, The Original Series,' which first aired in 1966. A lot has changed in the time since Captain Kirk fought a Gorn by hand in the original series. Star Trek is not merely science fiction, but is also known to challenge inequalities in society. However, 'Star Trek' is known for singlehandedly inspiring a generation of scientists and engineers whose work saw human exploration of the Moon and permanent laboratories in space.

My favorite ‘Star Trek’ movie reboot of the franchise in 2009 with an epic space adventure with the tagline, the future begins. The story begins following James Kirk's exploits as a cadet in ‘Starfleet Academy,’ but an attack on the Vulcan homeworld forces the cadets to become crew of the newly commissioned USS Enterprise. Without spoiling too much of the movie, the writers of the film employed a strange form of fictional matter called red matter, which appears to create black holes that can consume entire planets.

In the movie, the Vulcan homeworld has been attacked, and the planet's surface collapses inwards. Although visually impressive, Star Trek gets many of the black hole physics wrong. For one, the audience is meant to understand that red matter black holes are traversable. Unfortunately, traversable wormholes are merely a theory. They would require a super advanced civilization, and a number of notable scientific discoveries to permit travel. In fact, travel through a wormhole, if possible, would likely expose travelers to a serious dose of radiation, making the journey fatal to squishy humans like me.

On the other hand, ‘Star Trek’ explores some very interesting physics of black holes, specifically how a spacecraft might escape if it becomes trapped within the gravitational pull of a black hole. In one scene, the Enterprise is at maximum thrust, and is still being accelerated towards the black hole. In order to save the crew, the chief engineer Scotty suggests that the last option is to eject the warp core, and ride the shockwave from the explosion to safety. At best, it explores interesting science fiction concepts. At its worst, it makes some small, maybe forgivable errors, in scientific judgment for the sake of entertainment.

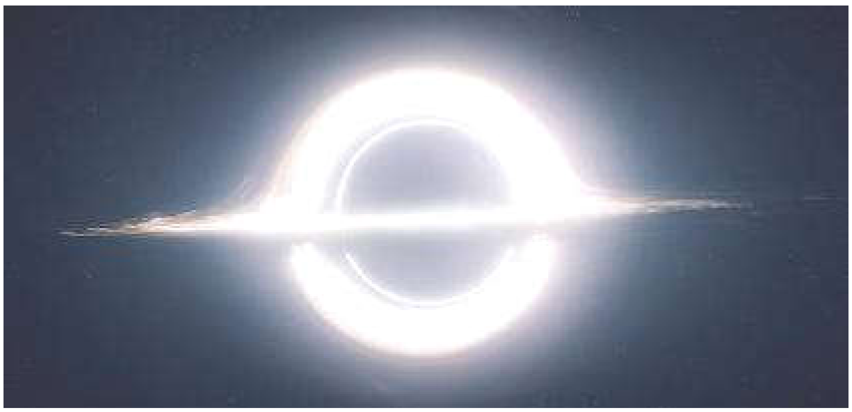


I enjoy watching ‘Star Trek’ and ‘Doctor Who,’ but often the treatment of science in these shows does not satisfy my sense of scientific consistency. One movie that did satisfy me was the 2014 movie ‘Interstellar,’ which presents the science of black holes as accurately as possible. There is still black hole physics that is unknown, like; ‘What happens when you cross an event horizon?’ Therefore, the moviemakers do engage in some speculation about what happens inside a black hole.

The black hole in Interstellar is a supermassive black hole named ‘Gargantua.’ Two planets are in orbit around the black hole at a safe distance, which is a reasonable possibility even though in the TV show ‘Doctor Who,’ they claim that planets orbiting black holes are impossible.

It is important to the plot of ‘Interstellar’ that ‘Gargantua’ is a supermassive black hole, since the strength of the tidal forces that could spaghettify an astronaut is weaker for black holes that are more massive. Although ‘Gargantua’ causes enormous tides on Miller's planet, the planet that orbits closest to Gargantua, the tidal forces are not strong enough to destroy the planet or the characters on the surface.

Another cool bit of science that ‘Interstellar’ gets right is the extreme time differences between Miller's planet and the spaceship that orbits farther away from the black hole. When 1 h passes on the planet, 7 years pass for the astronauts far from the black hole.



For me, the most exciting part of the movie is the view of the black hole, and the disk of material flowing around it. This view of the black hole incorporates most of the science of how light travels on curved paths around regions with gargantuan gravity.

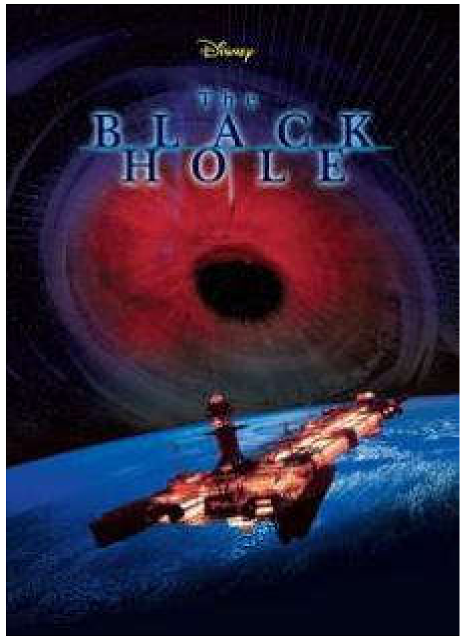
The black hole ‘Gargantua’ is extremely far away from us, but luckily the writers included a wormhole that allows a quick shortcut through space between Saturn and ‘Gargantua.’ Black holes exist, but wormholes probably do not; therefore, this part is science fiction. In the movie, they speculate that the wormhole was constructed by aliens. I do not know how to construct a wormhole but I am not an alien.

I will not spoil the ending of the movie for you. However, I will just let you know that there is a trip into the black hole.

What happens when they enter the event horizon is pure speculation, but who knows?

Maybe the screenwriters are correct.

In 1977, George Lucas presented his creation 'Star Wars,' a new hope to the world. It was packed with brand new special effects like fast-paced space battles and spectacular lightsaber duels. Sadly, 'Star Wars' did not include anything that we would really consider a black hole, unless you include the insatiably hungry Sarlacc. Therefore, we do not have much material from the 'Star Wars' Universe.



Fortunately, Disney was aware of the success of 'Star Wars,' and in 1979 decided to fund their own space opera called 'The Black Hole.' 'The Black Hole' was the biggest production in Disney's history with 20,000,000 $ spent on the budget, allowing them to create incredible visual effects. In the movie, the crew of the spacecraft 'Palomino' approaches a black hole on a scientific mission, only to discover another ship in orbit around it, the 'Cygnus,' a long lost vessel. The crew of the 'Palomino' must assess the dangers around the black hole, and decide, whether or not, to mount a rescue mission.

Disney's 'The Black Hole' was one of the first works of modern film making that attempted to recreate the environment around a black hole. Since we still do not have pictures of black holes, the filmmakers relied on scientists of the day to tell them what it might look like. Have a look at this scene from the bridge of the 'Cygnus.'

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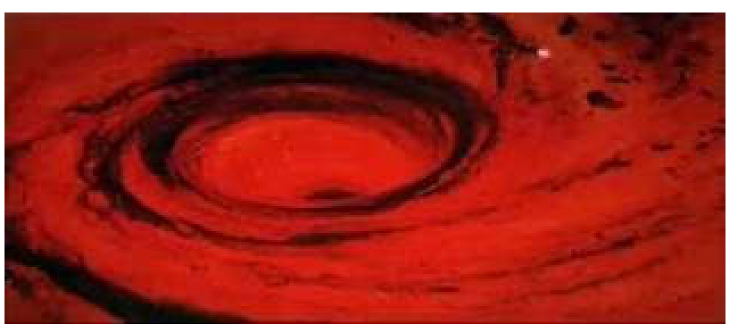
Video 1 : Scene from Disney's 'The Black Hole'

In order to make such a convincing illustration, the filmmakers relied on 20 years of work from scientists, like Roy Kerr, Roger Penrose, Werner Israel, and Stephen Hawking, whose names come up a lot in this course. They had been working on models of how black holes behave, and just what they might look like. In addition, the nearby black hole Cygnus X-1, which had then only been recently confirmed, became the namesake of this ship in the movie.



'The Black Hole' did many things correctly that other movies failed to do, like an accurate representation of an accretion disk for the time, and accounting for the time dilation effects around the black hole. However, in the film, the crew of the 'Palomino' descends past the event horizon, where their interpretation of the interior is almost certainly false. Instead of space-bending physics, as the 'Cygnus' descends into the black hole, it becomes a fiery realm like a portrayal of Dante's inferno. In reality, crossing the event horizon has dozens of dangers that would likely harm human explorers.

A lot has changed in the 40 years since Disney released 'The Black Hole,' especially related to black hole physics. We now know the strength of gravitational waves produced by merging black holes, and scientists are still developing theories to explain what the interiors of black holes might look like. This film introduces some of the interesting ideas about falling into a black hole, but there is one thing that I can tell you that none of these movies can. No one can tell you what happens when you cross a black hole's event horizon.

3 Connecting Gravity And Light

The relationship between light and gravity is fundamental to our understanding of black holes. In order to tie these ideas together, we will have to relearn the concepts of gravity, space, time, and light that we have been presented in our favorite movies, TV-shows, and other great works of art. Popular culture does not always get the science behind these concepts right, but it is surprising how scientific accuracy informs spectacular effects in movies like in Interstellar.

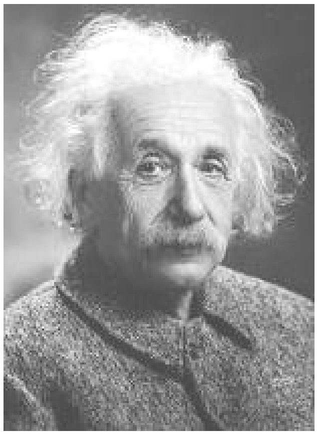


Illustration 4 : Albert Einstein

The scientific foundation for black holes has been built by hundreds of scientists contributing ideas throughout history, but one unmistakable scientist was responsible for the biggest developments, Einstein. Einstein's theory of gravity describes the gravitational attraction between massive objects, such as a star or a black hole, by associating the force of gravity with an equivalent curvature of space, sort of like a curved sheet.

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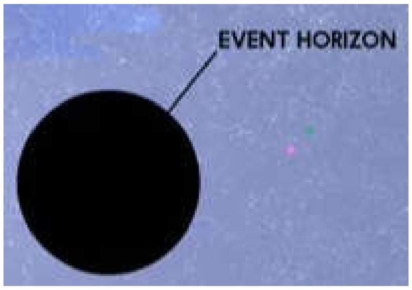
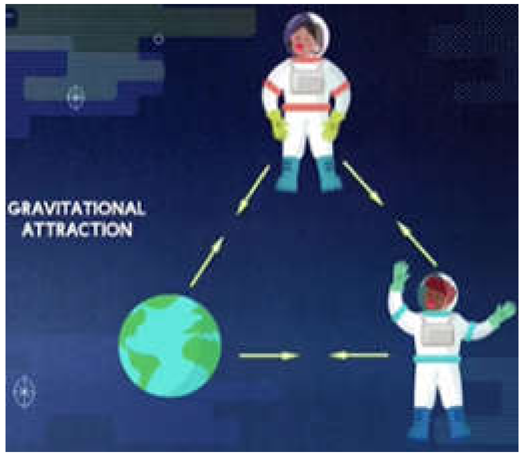
Video 2 : Demonstration of Gravity curving Space

All physical objects, including rocketships and individual particles of light called photons, travel on curved space-times similar to the curved path that these marbles follow. In this simple demonstration, we have an up and down direction defined by the Earth's gravity, which gives us the effect of the marbles orbiting around the central depression. In outer space, near a star or a black hole, we do not have Earth's gravity holding the marbles down on the curved sheet. Instead, we recognize gravity as curvature of space and time. This curved sheet provides valuable insight into how we can imagine the warping of space-time.



A black hole is a region of space where the force of gravity becomes so strong that the curvature of space-time prevents light from escaping. In this curved sheet model, imagine that a marble represents light. If the marble is aimed away from the center and tossed with a high enough speed, the marble is able to escape from the depression in the center. The region outside of a black hole or a normal star is like this, light that is emitted from objects in the neighborhood of a black hole are still able to escape. However, there is a special spherical boundary surrounding the black hole, which scientists call the event horizon. Once a marble falls within the event horizon, it must continue falling inwards. You could try to aim a marble outwards, but you would never be able to make the marble went fast enough that it can escape.

To some people, the concept of a black hole is terrifying. A black hole represents an inescapable vortex, whose strength can stretch astronauts into spaghetti, and even eat whole stars. Falling into a black hole is irreversible, and once inside, there is no opportunity to escape ever. To characterize this fear of black holes, people use the word melanoheliophobia, the fear of black holes. Much of that fear is misguided, as you will see; black holes come in various flavors that are not equally dangerous. That is good news if you are among those who suffer from melanoheliophobia, therefore, sit tight.



There is another misconception about black holes that they suck things towards them. All astrophysical objects like the Sun, the Earth, and black holes have gravity, and gravity is an attractive force. This means that just as marbles are attracted by gravity to the Earth, they too are influenced by the gravity of other objects. If we throw a marble directly towards the Earth, or the Sun, or a black hole, then just like the marble on this curved sheet, the thrown marble traveled directly towards the central depression. The strength of the gravitational depression depends on the mass of the object causing it. A star and a black hole with equal mass, even though they are different sizes, produce the same gravitational attraction far from their centers.

If this depression represents a star, then the stars surface is big, the marble enters the star and is burned up. Traveling directly towards a star is a recipe for crispy bacon. Now, let us pretend this depression represents a black hole. The gravity is exactly the same, but the black hole is much smaller than the star. Therefore, marbles can travel deeper into the depression before we lose track of it. When a marble enters the black holes event horizon, the curvature due to gravity prevents it from escaping, and it becomes lost to us forever. Even though directly traveling towards a star is a recipe for crispy bacon, traveling directly towards a black hole is a recipe for no bacon at all.

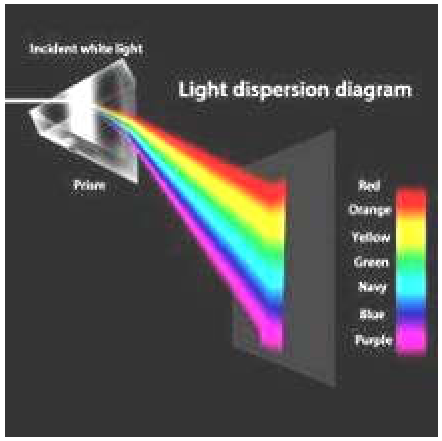
Instead of traveling directly towards a star or a black hole, we can instead travel safely around it in orbital paths similar to how the marble can be made to circle or orbit around the depression. Since the curved sheet in our demonstration has friction, the marbles eventually lose energy and fall in towards the center. However, in space, there is virtually no friction; therefore, it is possible for orbits to be stable for extremely long periods of time. For instance, the Earth has been orbiting the Sun for close to 5,000,000,000 years, and will continue to orbit it for several billion more years.

The idea that gravity is really just the curvature of space-time is a tough concept, which requires some knowledge of Einstein's theory of gravity called general relativity, which we will be introduced too later on in this course.

However, we can still get a taste of black hole physics by making use of an older less accurate description of gravity created by Sir Isaac Newton. In fact, several 18th century physicists were able to deduce the idea of a star, whose light cannot be seen using just their knowledge of Newton's theory of gravity along with the value for the speed of light. Since the concepts of light and gravity are so important for understanding black holes, we will review the basics of light, Newtonian gravity and some elementary physics principles as our starting point.

4 Getting On The Same Wavelength

It is impossible to discuss the concept of a black hole without first delving into the details about light or electromagnetic radiation. In the absence of light, we get darkness, or blackness, which is how black gets into the name black hole. Black holes do not allow light to escape from their interior, therefore, they appear completely dark. Our intuition regarding the properties of light can sometimes be misguided, therefore, let us discuss some of light's fundamental properties.



When a beam of white light is passed through a prism, the white light that enters is separated into a rainbow of colors spreading out to the other side of the prism. Each of the colors in the rainbow corresponds to a property of light called its wavelength. Wavelength is also related to the frequency of light, which is itself related to the energy of a photon.

4.1 Sound Waves

Another way to think about light is by way of an analogy to sound. Sound waves also come in different frequencies, which we call the pitch of a sound. Color is to light as pitch is to sound. For instance, I can make sound of a low pitch, or I can make sound of a high pitch, just as I can make low frequency light, like red, or high frequency light, such as blue.

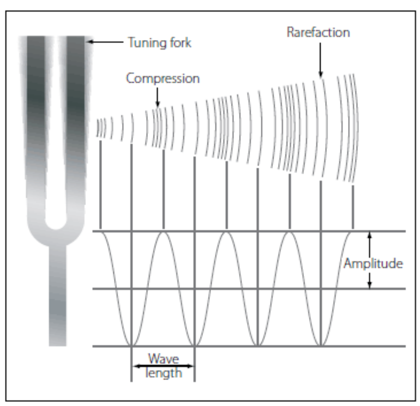


Illustration 5 : Sound waves formed by tuning fork

When a large tuning fork is struck, a low-pitched sound wave is created. The ends of the fork vibrate back and forth slowly at a low frequency. This vibration creates a pitch we hear as it is transmitted through the air. When we strike a small fork, a high-pitched sound is created as the end of the fork vibrates rapidly. Each of the forks tones are vibrating periodically, pushing the air molecules back and forth, which results in the creation of sound waves. Sound waves repeat at set intervals, separated by a distance, which is the sound wave's wavelength. Low-pitched sound waves have long wavelengths, while high-pitched sound waves have short wavelengths.

Additionally, sound travels at some finite speed, which we call the speed of sound, which is much slower than the speed of light. This is why you will sometimes see the source of a distant sound before you hear the sound itself. One of the most well-known examples of this is thunder that follows the lightning.

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Video 3 : Demonstration of a longitudinal wave

This type of wave is called a longitudinal wave. This is similar to how air molecules are pushed back and forth by a sound wave. Human hearing is limited to a range of pitches from about 20 Hz to 20,000 Hz, which means that it is possible to create sound waves that have a pitch that is either too high or too low for humans to hear. A sound wave that is too low for us to hear is called infrasonic. Moreover, some animals, like elephants, use infrasonic to communicate. Although a human cannot hear it, it is possible for them to feel infrasound as a vibration. Sound waves that are too high pitched for us to hear are called ultrasonic, and are also useful for navigation in animals like bats.

4.2 Light Waves

Just like sound waves, light waves are characterized by their properties wavelength, frequency, and propagation speed. The speed of sound depends on things like temperature and density of the air, and even the pitch of the sound. This is contrasted by light, which has a fixed speed in a vacuum and very little wavelength dependence travelling through a medium like air.

However, light waves travel at incredibly high speeds compared to sound waves. The speed of light is just a whisper shy of 300,000 km/s. The symbol *c* is used to denote the speed of light, which has a precise value of 299,792,458 $^{m}/_{s}$, or 2.9979 * 10^8 $^{m}/_{s}$. While sound waves are longitudinal compressions, light waves are actually a type of transverse electrical and magnetic wave. Scientists use the term electromagnetic radiation to describe light.

The longest wavelength of light that our eyes are capable of detect is approximately 700 nm long, which corresponds to a deep red. The shortest wavelength of light that we can see is approximately 400 nm long, a deep violet. Therefore, the range of light between 700 – 400 nm is often called visible light. This can be seen as a rainbow of colors. In order of longest to shortest wavelength, the colors are red, orange, yellow, green, blue, indigo, and violet.

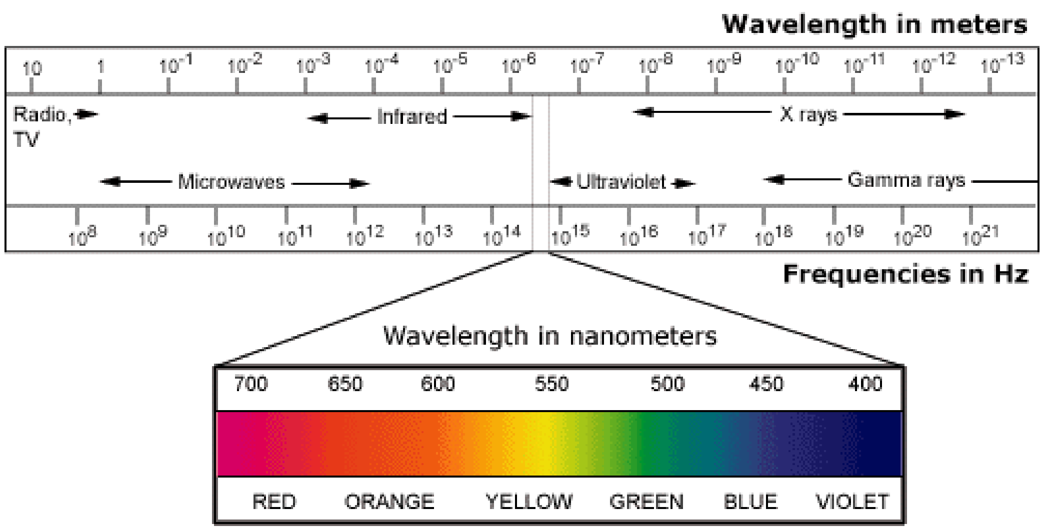


Illustration 6 : Electromagnetic Radiation Spectrum

Just as there are infrasonic and ultrasonic sounds that human ears cannot hear, there are colors that human eyes cannot see. The visible spectrum is only a narrow slice of the entire electromagnetic radiation spectrum. In order of longest wavelength to shortest wavelength waves, the bands in the electromagnetic spectrum range from radio waves to IR-light. This is followed by the familiar visible spectrum, then UV-light. As we approach shorter wavelengths, we have X-rays, and the shortest wavelength light, γ-rays.

Going from long wavelength electromagnetic light to shorter wavelengths is the same as going from low frequency light to higher frequencies. Even though there are all these types of electromagnetic waves, they all travel at the same speed, the speed of light.

4.3 Photons

We call individual particles of light photons. This is the same as saying that light is quantized; each photon is a small discrete packet of energy. The energy of a photon is related to its wavelength and frequency, and therefore, its color. With a beam of light, there are trillions of photons, each with their own energy. The energy that a photon carries is proportional to its frequency and inversely proportional to its wavelength. This means that X-ray photons, which have fast frequencies of oscillation, carry large amounts of energy.

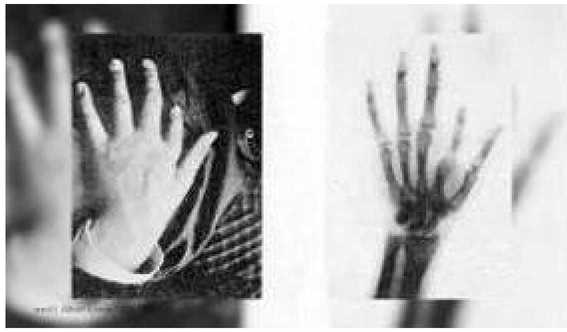


Illustration 7 : Normal photo and X-ray image of a deformed finger

As a result, X-ray photons have very short wavelengths, and can easily pass through human tissue, with the exception of bones. This allows doctors to take X-ray images of your skeleton.

On the opposite end of the energy scale, radio waves have low oscillation frequencies, and therefore, long wavelengths. They carry tiny amounts of energy. While exposure to X-rays can cause tissue damage, radio waves transport such small amounts of energies per photon that they are considered safe to use in modern telecommunications.

4.4 Wave-Particle-Duality

We have talked about light in terms of waves, discussing features like wavelength and speed. We have also talked about light in terms of particles or photons.

Which is it, are photons waves, or are they particles?

Well, the physical theories that describe light tell us that light behaves both as a particle and as a wave. It can take a little bit to get your head around the idea of light of being both wave and particle. In addition, it took scientists a long time to work this out, with arguments debating the nature of light and matter in the 1600s through until the early 1900s. This idea is known as wave-particle-duality. The duality tells that either light can act as a wave or as a particle depending on the situation, you are considering.

Now that we have covered the basics of light, let us take a look at how we can measure and use light to gain a greater understanding of black holes and the Universe.

5 Working With Light

For us to know anything about light, we need ways of making it, measuring it, and using it. In order to do all of these things, we creatures made of matter need methods of interacting with light. We know that matter is somehow responsible for the creation of photons, but until now, we really have not considered how. Light production falls into two major categories: incandescence and luminescence.

5.1 Incandescence

Illustration 8 : Incandescence

Incandescence is the production of light by anybody that contains heat energy, the energy of vibration. Incandescence is how filament light bulbs produce light. By warming the metal filament inside the light bulb using electricity, the metal grows hotter and hotter, emitting more and more light as the temperature increases.

The scientific principle of blackbody radiation explains how photons are created by the intense vibrations of atoms and electrons at high temperatures. Blackbody radiation applies to any object above absolute zero, even those that are very cold since even small atomic vibrations exist above absolute zero, the coldest possible temperature.

The theory of blackbody radiation describes how the oscillation of atoms in objects creates light waves. Atoms and electrons sloshing back and forth due to thermal vibrations or heat act as tiny emitters, creating oscillating electromagnetic fields. This wiggle of electromagnetic fields can be wrapped up in a neat little bundle we call a photon.

5.2 Luminescence

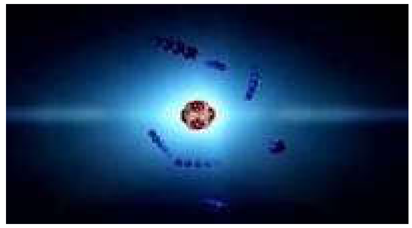


Illustration 9 : Luminescence

Luminescence is the production of light through atomic transitions, which are sometimes called cold body radiation. In a planetary model of an atom, electrons move in orbits around the nucleus. When an electron jumps from one orbit to another, it emits or absorbs a photon of specific energy to do this.

5.2.1 Fluorescence

Illustration 10 : Fluorescence

There are many subcategories of luminescent processes. Fluorescence converts UV-photons, which we cannot see, into visible light.

5.2.2 Phosphorescence

Illustration 11 : Phosphorescence

Phosphorescence releases energy stored in glowing of dark objects, and triboluminescence produces light when we chew on hard candies like lifesavers. Now, that we have some light to work with, let us make sure we can measure its properties.

5.3 Properties Of Light

When we want to take a measurement of light, what are we measuring?

We know that the speed of light is denoted by the letter *c*, and as a constant at just less than $3 * 10^8\ ^{m}/_{s}$. What is left is either to measure the wavelength, the frequency, or the energy that the photon packets carry.

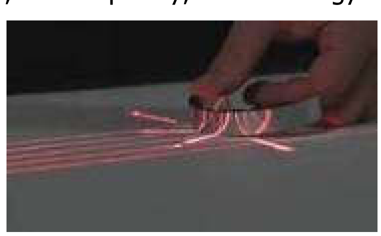


Illustration 12 : Red laser

A typical red laser emits a beam of photons with a wavelength of 650 nm. It could equally be advertised as having photons oscillating at a frequency of 460 THz, or even in terms of the photon energy, 1.9 eV. Electron volts may sound like a strange unit; one of many will come across in this course. It is defined as the amount of energy that is gained or lost by the charge of a single electron moving across an electric potential difference of 1 V. It is a minuscule amount of energy equivalent to about 1.6 * 10^{-19} J.

The naming and labeling of light can be confusing. The thing to remember is that a photon's energy, wavelength, and frequency can all be considered as equivalent ways to describe light. While a radio frequency photon emitted by a radio station is usually characterized by its frequency, say 102.9 MHz, an X-ray photon is usually characterized by its energy, say 1 keV.

Visible light photons are often described by their wavelength, between 400 nm and 700 nm. If you are given one of energy, frequency, or wavelength, there are some very simple mathematical relationships that allow you to determine the other quantities. The equation relating frequency and wavelength of a photon to the speed of light is:

$$c = \lambda f$$

Equation 1 : Relation between wavelength and frequency

Let us double-check the values we had for our red laser. We have been given its wavelength at 650 nm. Therefore, to determine its frequency, we simply divide the speed of light c by the wavelength λ.

$$f_{650nm} = \frac{2.99 * 10^{8}\ m/s}{6.5 * 10^{-7}\ m} = \underline{4.6 * 10^{14}\ Hz}$$

Remember, in order to calculate this properly, we need to express both the speed of light and the wavelength in the common unit of *m*. Therefore, a red photon with a wavelength of 650 nm has an oscillation frequency of 460 THz, exactly what I stated before.

How much energy is our 650 nm photon carrying?

Let us use our last answer of 460 THz to calculate the photon energy. This time, we need another simple equation that relates the frequency of a photon with the energy that it carries. The photon energy is given by the equation:

$$E = hf$$

Equation 2 : Energy of a photon

E stands for the energy, and *f* stands for the frequency of the photon. However, *h* is a new value in this equation. This *h* represents Planck's constant, named after Max Planck. It relates the frequency of a photon with its energy. *H* has a value of 6.626 * 10^{-34} Js. Now, our 650 nm wavelength photon, which oscillates with a frequency of 460 THz, carries with it the energy of:

$$E = \left(6.626 * 10^{-34}\ Js\right) * \left(4.6 * 10^{14}\ Hz\right) = \underline{3.0 * 10^{-19}\ J}$$

That is a tiny amount of energy. Every 650 nm wavelength photon carries an incredibly small amount of energy. However, bright light sources like lasers produce tremendous numbers of photons, which is why they pack enough punch to damage sensitive tissues like the retinas of our eyes.

Illustration 13 : Laser Safety Label

Hence, the laser safety label, that is a common phrase in laser labs, 'Do not look into the laser with your remaining eye.'

The relationships we have discussed here can be summed up in just three equations.

$$1) \quad E = hf$$
$$2) \quad c = \lambda f$$
$$3) \quad E = \frac{hc}{\lambda}$$

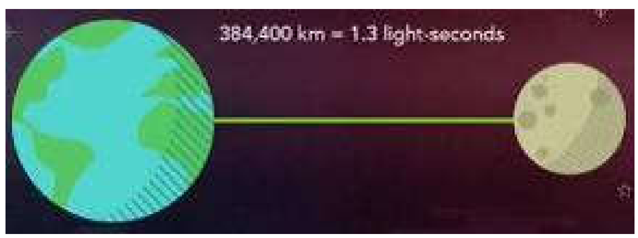
The first two we used, that we just run through, and the third is a combination of them. These simple relationships are modern discoveries relatively speaking, since they were developed in the early 20th century, during the quantum revolution. With these three equations, a technological revolution occurred that permitted the development of advanced optics and telescopes capable of measuring light from even the far reaches of the cosmos.

5.4 Speed Of Light And Space Distances

The speed of light is known to incredible precision. Since the speed of light is well known, it has become common for astronomers to measure enormous distances in space, in terms of the time it takes for light to travel in a given amount of distance. For example, the distance that light can travel in 1 s is known as a light-second.

$$\text{light} - \text{second} = 299{,}792{,}458\,m$$
$$= 299{,}792.458\,km$$

A number this large can be hard to wrap around your head. Therefore, let us compare this distance to one we can imagine, the distance from the Earth to the Moon.



The distance between the Earth and the Moon is 384,400 km, which is just a bit larger than one light-second is. We could use the unit *km*, which is getting a bit crazy at this point, or we could use the unit of light-second. In this new unit, the distance between the Earth and the Moon is 1.3 light-seconds. In other words, it takes a photon of light 1.3 s to travel from the Earth to the Moon.

If we now step up the size scale, and consider the Earth and our Sun, it takes light 8.3 min to travel from the Sun to the Earth. Therefore, we say that the distance is 8.3 light-minutes. Since the distance from the Earth to the Sun is so important in astronomy, astronomers also introduced a new distance called the astronomical unit, abbreviated to AU. An astronomical unit is the average distance between the Earth and the Sun.

$$1AU = 8.3\ \text{light} - \text{minutes}$$
$$\underline{= 149.6 * 10^{6}\,km}$$

Yeah, the measure of the distance in km is starting to get a bit crazy and messy. If we return to the speed of light measuring stick, continue to shift the sky skill further, we have had light-seconds and light-minutes, then a light-year is the distance light travels in 1 y.

$$\text{light} - \text{year} = \underline{9.5 * 10^{12}\,km}$$

Unlike this sound like a big distance, but the distance between the Sun and the next closest star, Proxima Centauri, is larger than this. Proxima Centauri lies 4.2 light-years away. The distance to the center of the Milky Way galaxy is close to 25,000 light-years. The final unit of distance we want to mention here is called a parsec.

$$1\ \text{pc} = \underline{3.26\ \text{light} - \text{years}}$$

It was defined in 2015 to be equal to 648,000 divided by π [AU].

This unit of measurement developed in the early 1900^s may sound familiar to some of you, from the beloved character in 'Star Wars' and 'New Hope.' 'Han Solo,' owner of the 'Millennium Falcon' brags to 'Luke Skywalker' and 'Ben Kenobi' that this ship that made the 'Corsal Run' in less than 12 pc.

On first hearing this, you might think that a parsec is a measurement of time, but this is obviously not the case. According to fun theory, the 'Corsal Run' is a heavily used smuggling route that normally takes 18 pc to navigate. However, Han claims he had shorten the journey by sketching a nearby black hole cluster called the mole. This path took him closer to black holes than others were willing to go, and shortened that route by 6 pc.

However, in the original script written by George Lucas, Han's line is to be delivered in such a way as to denote he is obviously lying in order to boast in front of Luke and Ben. Needless to say, the 'Millennium Falcon' did prove to be a fast ship. The way speed is portrayed in these films, depends not only on visual effects but also on sound effects. Yes, you heard that right: the Doppler shift.

6 Doppler Shift

Next up on our tour of the properties of light and sometimes sound, is an effect first explained by an Austrian mathematician and physicist, Christian Doppler in 1842. In a paper entitled, 'On the Colored Light of Binary Stars and some other Stars of the Heavens,' Doppler presented his theory that observed frequency of wave depends on both the emitted light, and on the relative speed of the source and the observer.

However, what does this mean?

Well, if we switch back to sound waves for a moment, we can use a real world analogy to explore this. I am sure many of you have been present as emergency vehicles or train pass by.

When this happens, what do you hear? Yes, you hear a siren, but what happens to the siren as an ambulance drives by?

At this point, please watch Astro-101_004.mp4

Video 4 : Demonstration of Doppler Shift on sound waves

This raising and lowering of pitch is known as the Doppler Effect, and as we hinted at earlier, it also applies to light. As light is emitted from a source, the waves being emitted can be squashed or stretched along the direction of motion. Therefore, if a star is moving towards us, the light waves moving ahead of the star can appear to be increased in frequency or decreased in wavelength. This translates as a shift towards the blue end of the electromagnetic spectrum. Conventionally, as the star moves away from us, the waves appear to be stretched resulting in longer wavelengths and a redder look to the star.

For light, the shifts caused by the Doppler effect are known as blueshift and redshift. Although we should note that this is not confined to the visible band of the electromagnetic spectrum. Both X-rays and radio waves can also be blue and redshifted. The colors just speak to the direction of the shift.

Illustration 14 : Binary Star System

While stars do not normally raise surrounding clouds, they are all moving around in space. Many stars that are observed in the night sky are actually in binary star systems. In such systems, we see stars in orbit around one another. If we view a pair of stars from the side, it will appear as though one star is moving towards us, while the other star is moving away from us. This relative motion is detected as blueshifts and redshifts that we detect from these stars.

Illustration 15 : Spiral galaxy NGC 6814

The same is true of galaxies. Spiral galaxies are found spinning and spiraling in space. In fact, our own galaxy, the Milky Way, takes about 240,000,000 years to complete one full rotation. When we look at other galaxies, we can measure the light emitted at various points across the disc to deduce the galaxy speed of rotation.

When measuring light from stars, we see a shift in light towards shorter wavelengths from the side of the galaxy approaching us; it is blueshifted. If we look at the other side of the disc, it is moving away from us, we can see a shift of light towards longer wavelengths; it is redshifted. It is interesting to note that while one of our closest neighbors M31, or the Andromeda galaxy, is rotating; we also see an overall blueshift of the whole galaxy, implying that M31 is moving towards us.

While there are many other examples of the use of redshift and blueshift in astronomy, the most well known Doppler shift in astronomy, triggered the idea of the expanding Universe. In the early 1900s, the prevailing theory was that the Milky Way, our own galaxy, was pretty much the extent of the Universe. In the early 1920s, an astronomer named Edwin Hubble was working at the Mount Wilson observatory in the USA. He was making measurements of the distances of various nebulas, only to find that some, including what was then known as the Andromeda nebula, were far too distant to be part of our own galaxy. Instead, these objects must be galaxies in their own right. This meant that the Andromeda nebula became known as the Andromeda galaxy, the one just mentioned a few moments ago.

Although the idea of multiple galaxies had been proposed as early as the mid 1700s, it is strange to think that the concept of galaxies is so new. This idea was only conclusively proven about 100 years ago. In 1929, Hubble continued these observations and found a relationship between the distance and the redshift of galaxies. Hubble found that galaxies that are outside of our local group of galaxies have light that is redshifted. Not only is the light redshifted, he also saw that the further away the galaxy is from us, the larger the change in wavelength or the larger the redshift.

If the change in wavelength is interpreted as a Doppler shift due to the motion, then Hubble's observations suggest that galaxies appear to move away from us. Galaxies that are further away from us are moving away from us at a faster speed. The modern interpretation of Hubble's observations is that the Universe is expanding, which it makes it look like galaxies are moving away from us.

The description of the expansion of the Universe is called 'The Big Bang Theory.' The Big Bang explains the evolution of the Universe after its beginning. 13,820,000,000 years later, we find ourselves here on the Earth learning about black holes. Speaking of which, if we want to understand black holes, we need to understand something about gravity. For that, let us start with the simplest version, Newtonian gravity.

7 Newtonian Gravity

Gravity is the force that keeps us standing on Earth's surface. It is the reason that a ball thrown upwards falls back down towards the ground. It was Newton who first realized that this force, gravity, does not just affect physical objects here on Earth, but is also responsible for the motion of the stars and planets. Gravity keeps the Earth moving in orbit around the Sun, and the Sun in orbit around the supermassive black hole at the center of the Milky Way galaxy. Gravity is a central principle in black hole physics, because it is gravity that gives black holes their extreme properties.

Until the year 1687, the year that Isaac Newton put forth his vision of gravity, no one had a clear understanding of what causes the attraction of objects towards the ground. A similarly mysterious force was also keeping the Earth moving around the Sun. Even in antiquity, humans understood that something held objects in place, but lacked the mathematical description. It was Newton who provided the first empirical description of how gravity works.

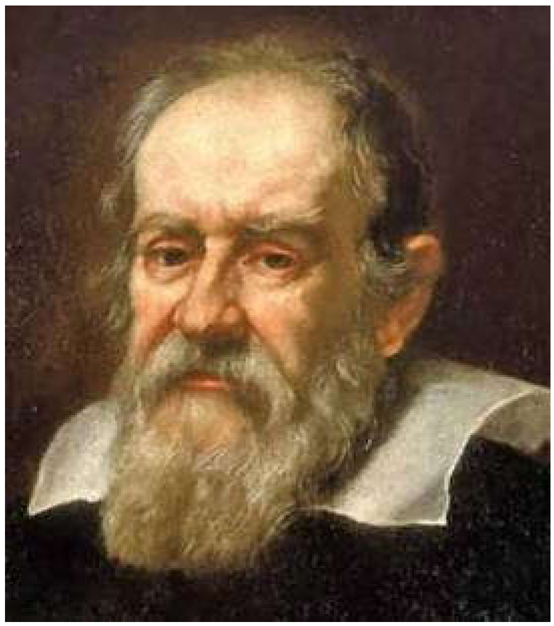


Illustration 16 : Galileo Galilei

Although Newton was the first to explain gravity mathematically, almost exactly 100 years earlier in 1589, Galileo Galilei was busy investigating gravity, and his observations greatly advanced our understanding of the interaction between objects and their masses. Galileo theorized that falling objects of different masses would fall at the same rate contrary to the Aristotelian belief that heavy objects fall faster than light objects.

Illustration 17 : Galileo's Experiment on Gravitational Force

It is famously claimed that to prove this idea, Galileo climbed up the Leaning Tower of Pisa, and dropped two cannon balls with different masses, one heavier and one lighter. He observed that if both cannonballs were dropped simultaneously they hit the ground at precisely the same time independent of their weights. Galileo made the mistake of assuming that the gravitational force was a constant between two objects, with no relationship to the distance between them. Historians disagree whether this experiment really took place, because it is first mentioned almost 65 years after it is supposedly took place in a biography of Galileo by Vincenzo Viviane.

One experiment done during Apollo 15's mission to the Moon demonstrates the principle that Galileo addressed. At the end of the last moonwalk, astronaut David Scott performed the same demonstration that Galileo did with a hammer and a feather in the vacuum of space. The result of course is visible in this famous video.

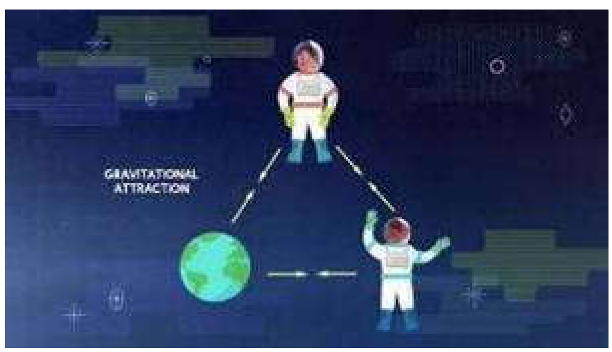
At this point, please watch Astro-101_005.mp4

Video 5 : Demonstration of Galileo's experiment on the Moon by Apollo 15 astronaut David Scott

Illustration 18 : Christiaan Huygens

Shortly after Galileo's death, mathematician and astronomer Johannes Kepler observed that planets trace ellipses through the solar system as they orbit the Sun. Kepler famously described the motion of the planets mathematically, laying the groundwork for the second last piece of the gravity puzzle, which was solved by Christiaan Huygens, who in the 1660^{s} described the law of centrifugal force. Together with the help of Edmund Halley, Christopher Wren, and Robert Hooke, Isaac Newton had all the clues he needed to piece together the mathematical description of gravity.

In 1687 Newton's book 'Philosophiae Naturalis Principia Mathematica,' which translates to 'The Mathematical Principles of Natural Philosophy,' laid the mathematical foundations to explain all of gravitationally related phenomenon, including apples falling from trees, and planets in orbit around stars.



Gravity is an attractive force between two objects that have mass. Any object that we talk about in this course, with the exception of light, has mass. The Earth has mass, I have mass, and you have mass. There is, therefore, a gravitational attraction between the Earth and me, the Earth and you, but also between you and me at any given time. The mathematical description of the force of gravity needs to take into account the mass of both objects, and also the distance between them. In order to get useful information out of any equation, we also need a universal gravitational constant to tell us how strong the force will be given the masses and the distances.

Let us call them mass of the larger object *M*, and the mass of the smaller object *m*. The distance between the two objects will be measured by *r*, and the universal gravitational constant will be denoted as *G*. The force of attraction between two objects will be directly proportional to their masses, but inversely proportional to the square of the distances separating them. Direct proportionality means that the force *F* will be:

$$F = \frac{GMm}{r^2}$$

Equation 3 : Newton's universal law of gravitation

It calculates the force between two objects, no matter what their masses are. In order to use this equation, we need to consider the units of each term.

$$G = 6.67 * 10^{-11} \left[\frac{N * m^2}{kg^2} \right]$$

That is a mouthful. To make these units cancel out, you can see that *M* and *m* will cancel out the kg^2 term, and that r^2 cancels out the m^2 term, leaving behind Newton.

Notice how tiny the gravitational constant is. If we ask ourselves, 'how much attractive forces felt between two objects each weighing 1 kg and separated by 1 m,' the answer of course is:

$$F = 6.67 * 10^{-11} N$$
$$\underline{= 66.7 pN}$$

For comparison, 67 pN is about how hard you have to pull the two ends of a DNA-molecule in order to have them unravel. However, gravity acts on much larger scales, and is, therefore, comparatively weak.

Let us compare 67 pN to the force of gravity that I feel due to the Earth. Since Earth weighs $5.97 * 10^{24}$ kg, and I weigh about 75 kg, in order to calculate the force of gravitational attraction, I will replace *M* with Earth's mass and *m* with my mass. We also need to know how far apart the center of the Earth is from the center of me. Let us take the radius of the Earth's surface to be *r*, and replace it with a value of 6,378.1 km, which we have to convert into m.

$$F = \frac{6.67 * 10^{-11} * 5.97 * 10^{24} * 75}{6{,}378.100} \left[\frac{N * m^2 * kg * kg}{kg^2 * m^2} \right]$$
$$\underline{= 735 N}$$

Therefore, I am being pulled towards the center of the Earth with a force of 735 N. The unit of force N is sometimes difficult to put into context. It is related classically with the acceleration of a mass by Newton's second law:

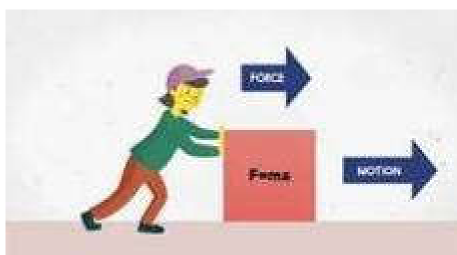


Illustration 19 : Newton's second law

It relates the force on a mass to how quickly the mass accelerates. Since I feel the force of gravity as 735 N, I can calculate my acceleration due to gravity by dividing my mass, which results in an acceleration of $9.798\, m/s^2$. You might recognize the coincidence. The acceleration I feel is very close to the value of Earth's acceleration due to gravity, which is often denoted as *g*, and has an average value of $9.807\, m/s^2$.

The reason that these two dot numbers are different is because the strength of Earth's gravity varies over a surface. For example, you weigh about ½ % heavier, when you are at the Earth's poles than you do when you are along its equator.

In fact, Earth's gravity varies a lot over its surface, because of the different densities of rocks and the different geography of regions. Earth's gravity diminishes by about $^1/_5$ % from Earth's surface to an altitude of 5 km. Therefore, your height above or below sea level is also a factor. However, geology can account for another $^1/_{100}$ % difference in gravity.

At this point, please watch Astro-101_006.mp4

Video 6 : Differences in gravity due to geology

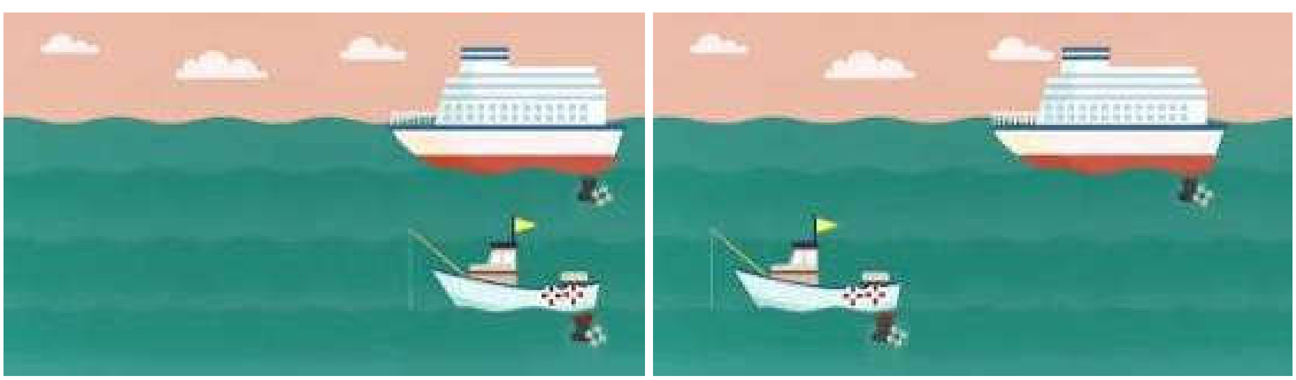
Illustration 20 : GRACE Satellites

The data was collected by a pair of satellites called GRACE, the 'Gravity Recovery and Climate Experiment.' GRACE uses changes in Earth's gravity to measure changes to huge masses of ice in our polar regions. If gravity there decreases, scientists can determine how much of the glacial ice is melting in those regions, and this data can even tell where vast underground reservoirs of water are filling up.

If Newton had accomplished nothing but the mathematical formulation for the law of gravity, he would still go down as one of history's greatest physicists. However, he contributed much more to our understanding of the Universe. He revolutionized our understanding of motion, forces, and mechanics with his three laws of motion. Newton's three laws can be stated in the following way:

Newton's first law states: 'An object at rest will stay at rest unless a force acts upon it. An object in motion, especially uniform motion, will stay in motion unless a force acts upon it as well.' It is interesting that we distinguish between an object at rest, and an object moving with a uniform velocity. As we get deeper into this course, you will understand that these two examples, an object at rest and an object in uniform motion, are themselves within what we call an inertial frame of reference. We could also think about a rocket moving in outer space at a constant speed. Unless the rocket was firing its thrusters to exert a force in the opposite direction, the rocket will continue moving at a constant speed forever. Newton's first law is also called the 'Law of Inertia.' Inertia is the resistance that an object has to changing its state of motion.

Newton's second law states: 'An object acted upon by a force will experience acceleration in proportion to its mass.' This is the famous formulation, which is described by equation 3 that we used earlier. Any force acting on an object will produce acceleration in proportion to the mass of the object. Therefore, for any given force, a small mass will accelerate quickly, but a large mass would accelerate slowly.



Think about it using a small motor on both a small boat and a huge ship. The motor delivers the same amount of force, but the ships accelerate at much different rates.

Newton's third law states: 'For every action there is an equal and opposite reaction.' Newton's third law is a little hard to wrap your head around, but it basically means this:

Any force, which is imparted on an object, must also be imparted equally upon another. In other words, for all the force of Earth's gravity pulling upon me, I am also exerting a force pushing down upon the Earth.

This point confused me for some time as a student.

Why is it that we say Earth gravity has a value of $9.807\, m/s^2$?

That is a measure of acceleration. Well, when I am standing still on Earth, Earth surface is not actually accelerating anywhere. My acceleration is zero. The truth of the matter is that the strength you exert to stand is the force pushing back on the Earth. The net force between you and the Earth ends up zero.

What about if you are not standing on Earth's surface, but you have gone sky diving, and you are falling freely through the air?

In this case, you are accelerating at $9.807\, m/s^2$, but you should also consider that Earth is accelerating towards you. The forces are the same for you and for the Earth, but the acceleration of the two is different, because you and the Earth have vastly different masses. In this case, Earth would accelerate towards you at a tiny rate of about $1.23 * 10^{-22}\, m/s^2$.

Newton's second law of motion means that when we apply a force to an object, the object will accelerate. Therefore, when you apply a gravitational force to an object, it will accelerate. If we take Newton's law of universal gravitation (see equation 3), and set the force equal to F in Newton's second law $F = ma$, then m on both sides of the equations cancels each other out, resulting in the equation:

$$a_g = \frac{GM}{r^2}$$

Equation 4 : Acceleration due to gravity

This equation provides a simple way of calculating the acceleration due to gravity. When I stand on the surface of a planet that has a radius r, and a mass M, then the acceleration due to gravity at the surface is simply given by the above equation. If the planet is Earth, we use the symbol G to represent the acceleration due to gravity. We say that a body has a gravitational field when it has the potential to accelerate nearby objects towards it. Newton's equations are robust enough to send rockets to other planetary bodies. In order to do so, we need further to tie the concept of gravitational potential energy, the energy required to climb through a gravitational field in order to calculate escape velocity.

8 Escape Velocity

Before we go into orbit, let us discuss an important difference in physics. The difference between weight and mass. On Earth, we say that the two are equivalent. I weigh 75 kg, and I have a mass of 75 kg. However, that only works here on Earth, in Earth gravity. On planets with different gravity from Earth, weight and mass have different values. Mass is a property of an object that can describe as the ability for that object to resist acceleration. Weight on the other hand depends on a local gravitational field. Mass always stays the same. If my mass is 75 kg, I will be 75 kg whether I am here on Earth, on the Moon, or somewhere in deep space. Nevertheless, weight is actually a measurement of the force felt by an object within a gravitational field, which means that weight can change in different gravities. It is a product of the mass in the local gravitational field, therefore:

$$weight = m * g$$

Equation 5 : Relation between mass and weight

On the Moon where gravity is roughly $^1/_6$ of Earth's gravity, my mass is still 75 kg, but my weight is reduced by a factor of six. That means that on the Moon my weight would be 12.5 kg, even though my mass is still 75 kg.

What does it mean to be weightless if weight depends on the local gravity?

Well, imagine a region of space so far from stars and planets that the local gravitational field is very close to zero.

What would someone with a mass of 75 kg feel when there is zero gravitational force on them?

They would feel a weight of 0 kg.

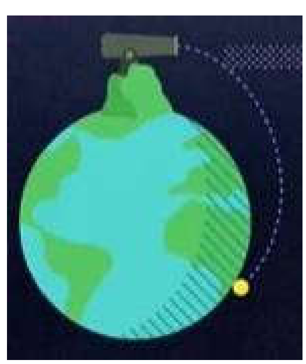
Illustration 21 : Astronaut, freely floating in space

Therefore, when astronauts are floating freely in space, are they weightless?

No, it is a common misconception that astronauts experience weightlessness when they are above Earth's atmosphere where gravity is weak. In fact, there is still enough gravity in the environment around Earth that they have a measurable weight. However, this is different from experiencing free fall. Acceleration in a gravitational field that is not restricted by any other forces. Astronauts feel weightless, because both the spacecraft that they are in and the astronauts themselves are in a state of free fall above the Earth. A body is in free fall whenever gravity is the only force acting upon it.

If either I release a ball, low or from up high in space, the only force acting on the ball while it is moving is gravity. When it is moving, it is in a state of free fall and experiences weightlessness. Since the force of gravity acts on it, the ball accelerates and moves towards the Earth until it hits the Earth's surface.

What do you think would happen when the ball is thrown horizontally?



Newton was the first to imagine what would happen if you climbed a tall mountain in order to fire a cannonball horizontally. Newton reasoned that the cannonball would curve towards the Earth due to gravity. If the cannonball was fired at a faster speed, it will go a longer distance. Eventually, if the cannonball could be fired fast enough, it would fall towards the ground on a curved trajectory that matches the curvature of Earth's surface. This was the first time someone had reckoned about orbital motion.

This is very similar to how flying is described in Douglas Adams's ‘A Hitchhiker's Guide to the Galaxy,’ where it is stated, there is an art to flying, or rather, a knack. The knack lies in learning how to throw yourself at the ground and miss. When an astronaut orbits the Earth in the ISS, the only force acting on the astronaut is gravity. The astronaut is traveling in a stable orbit around the Earth. Therefore, although gravity is pulling on the astronaut towards the Earth, the circular motion makes it possible for the astronaut to miss the Earth. One way to experience weightlessness without being in orbit or at a vast distance from the Earth is to fly in an airplane on a parabolic trajectory. Special aircraft that can withstand many times the force of gravity navigate to a high altitude before climbing into an inverted parabolic flight path.

During the arc of the parabola, the airplane and the occupants within it only experience the force of gravity, and therefore, they feel weightless. These moments feel like zero gravity but they only last about 20 s. The airplane cannot stay in freefall for very long for obvious reasons.

Illustration 22 : Saturn V start (Apollo 11 mission)

Rockets like the Saturn V that carried the crew of the Apollo 11 mission to the Moon must expend energy to climb through Earth's gravitational field. The speed of a spacecraft dictates how high it will go in a given scenario.

How much energy is required for a rocket to escape from a planet entirely?

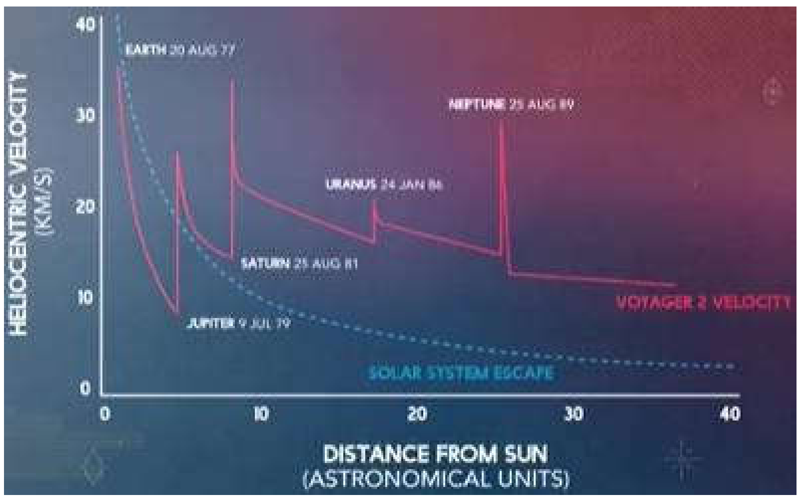
Let us consider an example of a rocket escaping from Earth. Kinetic energy is the energy associated with the speed of an object, which is supplied to a rocket by burning fuel and expelling it from the rocket's nozzles. The energy required to break the gravitational grasp of a planet like Earth depends on the mass of the planet as well as its size. When a speed is associated with kinetic energy of a departing rocket, we call it the escape velocity. Earth has an escape velocity, which is roughly 11.2 $^{km}/_{s}$, which is more than 40,000 $^{km}/_{h}$. However, let us not are too carried away, getting to space is much more complicated than merely getting a vehicle to the right speeds.

This calculation considers the pure physics involved in climbing out of a gravitational potential well. We ignore otherwise important factors like air resistance. 11.2 $^{km}/_{s}$ is the instantaneous velocity you would need traveling directly upwards from Earth's surface in order to escape Earth’s gravitational well. At sea level, 11.2 $^{km}/_{s}$ is equivalent to Mach 33, which is fast enough to make the air around the spaceship into a boiling plasma, therefore instead, rockets accelerate out of our atmosphere starting from a standstill.

Although we used Apollo 11 to introduce you to the concept of escape velocity, it is worth pointing out that in order to reach the Moon, the astronauts never exceeded Earth’s escape velocity at all. The Moon is gravitationally bound to Earth, and a voyage there has not escaped from Earth's gravitational sphere of influence. The Moon itself is also trapped within Earth’s gravitational well.

Illustration 23 : Voyager 2

Out of all the spacecraft launched by humanity, only a few have achieved Earth's escape velocity. Those spacecraft, which travel to other planets in our solar system, but a small subset of spacecraft have voyaged well beyond the Earth's grasp, and escaped from the gravitational pull of the entire solar system. One such spacecraft, Voyager 2, witch launched in 1977, is now considered to be an interstellar traveler.



The red line in this graph represents the changes in speed experienced by Voyager 2 from 1977 to 1989 on its journey past the outer planets. In order for Voyager 2 to achieve escape velocity from our solar system, it needed a gravity assist from Jupiter. A gravity assist is a way for a space probe to boost its kinetic energy by stealing the orbital energy from a heavy body like Jupiter. Over the course of Voyager 2's transit through the solar system, it was repeatedly boosted by encounters with planets Saturn, Uranus, and Neptune.

At present, Voyager 2 is traveling at 15.4 $^{km}/_{s}$ on its way to the outer most edge of our solar system. By contrast, the fastest humans have ever traveled was accomplished by the crew of Apollo 10 in 1969, achieving a top speed of nearly 11.08 $^{km}/_{s}$. However, their speed record was on their way back through Earth's atmosphere, and not on the way out.

Illustration 24 : New Horizons

However, even faster than the Voyager spacecraft, the current speed record held by a human object is the New Horizons probe, which took pictures of Pluto in a flyby in 2015. New Horizons accelerated away from Earth, achieving a whopping 16.26 $^{km}/_{s}$, making it the fastest spacecraft ever launched.

$$\frac{GMm}{r} = \frac{1}{2} m v_e^2$$
$$\frac{GM}{r} = \frac{1}{2} v_e^2$$

Equation 6 : Escape velocity, derivation

Deriving the formula for escape velocity is relatively straightforward. It involves setting the gravitational potential energy equation of an object on the surface of a body equal to its kinetic energy. Since the *m*, which represents the mass of the object you want to move, appears on both sides of the equation, we can eliminate those from the equation altogether. This means that the escape velocity of an object does not depend on its own mass.

$$v_e = \sqrt{\frac{2GM}{r}}$$

Equation 7 : Escape Velocity

We can finally rearrange the terms of this equation, solving for v_e, the escape velocity. Therefore, increasing the mass of a body will increase its escape velocity, and decreasing the radius of a body will also increase its escape velocity. In order for spacecraft to escape from Earth, escape velocity is required to ensure the gravitational potential well can be climbed. In fact, if you would like to explore these ideas further, we have created an escape velocity calculator that you can use to plan a mission across the solar system.[1]

What could escape velocity possibly have to do with black holes?

The answer is something sinister, something dark.

9 Dark Stars

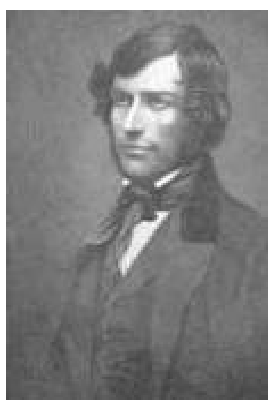


Illustration 25 : John Michell

If I asked you who first proposed the idea of a black hole, who would be your first guess?

Perhaps Albert Einstein, Stephen Hawking, or Carl Schwarzschild. While these scientists have had a huge impact on black hole astrophysics, the idea of a strong gravitational field altering light was first described by an often-overlooked clergyman named John Michell. John Michell was the first to describe an object whose escape velocity exceeded the speed of light, which they called ‘Dark Stars.’ The year was 1783, falling very close to the midpoint between Newton's theory of universal gravitation and Einstein's theory of special relativity. John Michell, a retired professor of geology at Cambridge, was working as director of Thornhill in England, and he used his spare time to fuel his scientific curiosity. In particular, working with theories of light and gravity.

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[1] Velocity Calculator

Illustration 26 : Michell's suppose

John suppose that light consisted of a particle, which is a topic of hot debate at the time, and that gravity acted upon the particles of light in the same way that gravity acts on all objects. At the time, there was no experimental evidence to think otherwise, and Newton's gravity was considered a universal law. Rector Michell reasoned that objects within gravity would require a certain amount of speed to reach infinity, the speed, which we now call escape velocity. In addition, that for particularly small and dense objects, the escape velocity might exceed the speed of light.

Illustration 27 : Pierre-Simon Laplace

The French mathematician, Pierre-Simon Laplace, came up with the same idea in 1796, which he referred to as an 'Invisible Body.' Although Laplace first wrote about invisible bodies in 1796, more than 10 years after Michell, this idea was probably developed independently since there was very little scientific communication between France and England in that period.

Let us have a look at the escape velocity equation again, but this time let us do something silly. Instead of solving for the velocity, v_e, let us solve where the radius of an object with mass m whose escape velocity is equal to the speed of light, just as rector Michell did.

We will denote the speed of light as the letter C and use it to replace v_e. In order to solve for the radius r, we first need to square both sides of the equation, therefore, that c becomes c^2, and the square root sign on the right-hand side goes away. Then we can multiply both sides of the equation by a factor of r divided by c^2, leaving us with the solution in terms of the radius.

$$v_e = \sqrt{\frac{2GM}{r}}$$

$$c = \sqrt{\frac{2GM}{r}} \quad | \text{square both sides}$$

$$c^2 = \frac{2GM}{r} \quad | \text{multiply with } \frac{r}{c^2}$$

$$\underline{r = \frac{2GM}{c^2}}$$

What this means is that for an object of mass M, we can calculate how small it would need to be in order to have an escape velocity equal to the speed of light. Let us try Earth's mass for fun. Inserting $M = 5.972 * 10^{24}$ kg into the equation, yields a radius of a puny 8.87 mm, like a tiny ball with less than 1 cm radius. Therefore, if this ball weighed the same as the entire Earth, it would have an escape velocity equal to the speed of light at its surface.

Our Sun's escape velocity is 617.7 $^{km}/_{s}$ given the solar mass and the average solar radius. In order for the Sun's escape velocity to increase to the speed of light, or 300,000 $^{km}/_{s}$, its radius would have to be reduced from 695,700 km to a radius smaller than 2.953 km.

What would the Sun look like if it were compressed to 2.953 km?

With its escape velocity equal to the speed of light, light would no longer escape from it, therefore, the Sun would appear dark. In addition, any light falling towards the Sun would disappear completely the moment it crossed the Sun's dark surface. In fact, nothing could escape from the object surface, because we know that the speed of light is an upper limit in our Universe. Using only classical physics, Michell was the first to describe 'Dark Stars' by trying to determine a method for measuring the distance and brightness of stars. Instead, he invented the first description of a black hole, an object massive enough to prevent light from escaping it. Additionally, Michell also predicted one of the most interesting results in black hole physics. You see, the equation that we naively replaced escape velocity for the speed of light, with that equation comes up again once we encounter Einstein's general relativity as a solution for the event horizon of the simplest kinds of black holes, Schwarzschild black holes.

10 What Is A Black Hole

The basic idea behind a dark star only requires knowledge of 18th century physics. If a star is dense enough, its escape velocity will be the speed of light, making it impossible for light emitted by the star to escape the stars gravity. The idea of a dark star, as proposed by John Michell is not correct, but it is still important since it introduces some ideas that apply to black holes even in modern theories. The problem is that the concept of a dark star uses Newton's older theory of gravity instead of Einstein's newer theory. That being said, Newton's theory of gravity is a pretty good approximation to Einstein's theory of gravity, when gravity is weak. It was good enough for us to plan a mission to the Moon, for instance.

When I mean by weak is this. Calculate the escape velocity from a planet or star, and compare the value of its escape velocity to the speed of light. If the escape velocity is tiny compared to the speed of light, then we say that gravity is weak, and Newton's theory of gravity is a good enough approximation. For example, the escape velocity from the Earth is 11.2 $^{km}/_{s}$, but the speed of light is approximately 27,000 times larger. Since the escape velocity from Earth is so small compared to the speed of light, Newton's gravity is good enough for most calculations near the surface of the Earth.

However, if the escape velocity is larger, say 10 % of the speed of light or larger, that means that Newton's theory of gravity is no longer sufficient to calculate the strength of gravity. Since Einstein's equations correctly describe relativistic effects at high speeds, they improved on Newton's theory of gravity. This means that we can predict what happens in situations with strong gravity.

10.1 Theory Of General Relativity

Einstein's theory of gravity is called 'The Theory of General Relativity.' In general, relativity, mass, energy, and angular momentum are all responsible for creating curvature in space-time. The curvature of space-time then causes planets, stars, and light to travel on curved paths.

To create a dark star, we might start with a large star, and compress it inwards to make it smaller and denser while keeping the amount of mass unchanged. As the star shrinks in size, the escape velocity from the surface becomes faster and faster until it becomes equal to the speed of light. At this point, Newton's theory of gravity just predicts that light will not be able to escape from the star, and it will appear dark.

However, the predictions from Einstein's theory of gravity demonstrate a so-called dark star would exert a much stronger force due to gravity than predicted by Newton. This additional inwards gravitational force makes it impossible for a start to have a stable size. In order for stars to exist, there is a delicate balance between its gas molecules, which exert a net outwards pressure that is exactly balanced by the attraction of gravity, allowing stars to stay the same size over time. When a star gets so small, that its escape velocity is the speed of light, then the required outward gas pressure is infinite. There is no way to create infinite gas pressure, therefore, the star is unstable and begins collapsing inwards.

10.2 Event Horizon

A black hole is what remains after stars are unable to resist gravity and collapses inwards. A black hole does not have a surface, but there is a special boundary that surrounds a black hole called an event horizon. In the case of the simplest black hole, the event horizon is a sphere with a radius called the Schwarzschild radius with the value:

$$r_{EH} = \frac{2GM}{c^2}$$

Equation 8 : Schwarzschild radius (Event horizon)

The amazing thing about the formula for the event horizon radius is that it is exactly the same equation that Michell derive for the radius of a dark star. The event horizon radius is a boundary for light rays. If an astronaut shines a flashlight outside of the event horizon, the light rays can escape from there and be seen by astronomers far away from the black hole. However, if the flashlight is at or inside of the event horizon, all light emitted will be trapped inside of a black hole. In addition, it is not just light, massive objects like cakes, or rockets, or astronauts, can escape as long as they are outside of the event horizon radius, and their rocket is good enough, but if a cake-eating astronaut crosses the boundary defined by black holes event horizon, no escape is possible.

The name black hole did not enter a common usage until 1967, where it was popularized by John Wheeler. Before then, astronomers used the name 'Totally Gravitationally Collapsed Objects' to describe black holes. This is an accurate phrase, but difficult to say. Therefore, it is not surprising that the name black hole caught on so quickly with scientists and science fiction writers alike.

The distinguishing difference between Michell's dark stars and black holes, as they are described in general relativity, is whether or not the star within the dark boundary maintains a surface. Michell did not consider what would happen to the surfaces of a star when its escape velocity reaches the speed of light. Scientists now believe that the creation of an event horizon causes all the material hidden behind it to continue collapsing inwards with no chance of a stable surface.

10.3 Other Dark Objects

Illustration 28 : Horsehead Nebula

There are other dark objects that astronomers make reference to, but they are not black holes. For instance, there are dark nebulas, which consist of clouds of cool molecules and dust that block out passing light. These types of nebula can be observed if they lie between us, and a bright source of light, since we will see that sunlight is blocked out by the nebula. One famous example is the Horsehead nebula. The Horsehead is a dense, cool cloud that blocks out the red light that has admitted behind it, allowing us to see it. In addition, dust emits IR; therefore, we can detect dust clouds if we use an IR-telescope.

10.4 Dark Matter

Dark matter is a hypothesized type of matter that was introduced to explain the motions of stars, gas, and galaxies. Dark Matter is a type of matter that does not emit light, which means it cannot be observed directly. However, dark matter does have mass; therefore, there is a mutual gravitational attraction between dark matter, the stars, and gas in the galaxy. The gravitational attraction of the dark matter affects how the stars in the galaxy move, allowing scientists to infer the existence of dark matter by their observations with theoretical models.

Illustration 29 : Vera Rubin

In the 1970s, Vera Rubin, observed spiral galaxies and measured the speeds of the stars. She showed that the fast speeds of these stars imply the existence of dark matter. A tiny amount of the dark matter could be black holes, but most of the dark matter is a type of particle called a 'WIMP,' which means 'weakly interacting massive particle.' Physicists are trying to detect WIMPs using the 'Large Hadron Collider' in Geneva, Switzerland, and 'SNOLAB' in Sudbury, Canada, as well as other laboratories. So far, the dark matter (WIMPs) has not been detected. The main thing that dark matter and black holes have in common is that they are both detected by observing their gravitational interactions with luminous objects.

10.5 Dark Energy

Dark energy is the name for another mysterious force, which appears to act in opposition to the force of gravity. When astronomers measure galaxies far, far away, they measure that the most distant galaxies appear to move away from us more quickly than galaxies that are close. This is one of the pieces of evidence that our Universe is expanding from a moment in history referred to as 'The Big Bang.'

Since all these galaxies have mass, they are gravitationally attracted to each other, and we might expect that the rate of the Universe's expansion should slow down over time. Instead, there is evidence that the expansion is speeding up, as if there were a repulsive force like a very large scale somewhat anti-gravity. This force called dark energy has nothing to do with black holes. However, there are some theorists who have considered types of stars that have some dark energy in them to help combat gravitational collapse.

10.6 Dangers

Black holes may give some people melanoheliophobia, but in most ways, they are no more dangerous than any other star in the sky. For example, entering into a black hole is dangerous, once you pass through the event horizon, you cannot get out, but if you enter into a star, the hot gas would burn you up too. I would say they are both equally dangerous. There are safe ways to visit a star or a black hole. Instead of traveling directly towards a black hole, you could instead orbit the black hole just as you can orbit around a star. For example, the Earth orbits around the Sun in a safe stable orbit. Similarly, the Earth could orbit a black hole with the same mass as the Sun and at the same distance, making the orbit just as safe and stable as it is now. Unfortunately, it would be very cold around a black hole, since the sunlight that warms us would no longer be present. There is nothing about the black hole's gravity that would suck in the Earth.

10.6.1 Accretion Disc

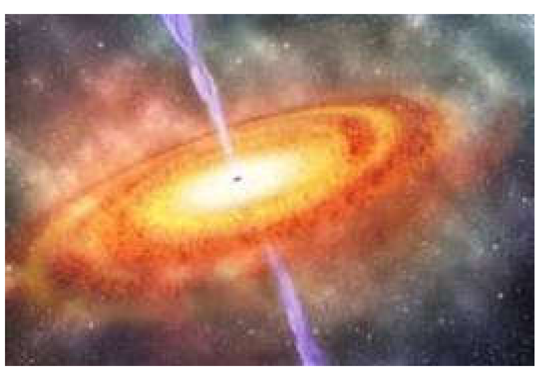


Illustration 30 : Accretion disk around a black hole (Artists view)

Black holes can become dangerous if they are surrounded by an orbiting disc of hot gas, which looks similar to the rings of Saturn. The disc of gas could emit high energy X-rays. Therefore, if you were to approach the black hole's disc, you could receive an unhealthy dose of radiation. For this reason, in the movie 'Interstellar,' the script writers decided to make the disc of gas orbiting their black hole be relatively cool, therefore, that it only emits visible light, and no harmful X-rays.

10.6.2 Tidal Force

The tidal force, which is a difference in the strength of gravity at different locations, can become very strong around a black hole. In fact, when it comes to the tidal force, the smaller a black hole is, the more dangerous it becomes. An astronaut venturing too close to a small black hole would be stretched by gravity into long thin spaghetti-like strands.

10.6.3 Isolated Black Holes

Out of all the types of black holes, the most dangerous are thought to be the isolated black holes. In isolation, a black hole does not have a companion star or an orbiting disc of gas, making them extremely difficult to see due to their difficulty of detection. It is possible that you could accidentally stumble across one, and inadvertently cross into its event horizon while you are exploring the Universe.

10.7 Gravitational Lensing

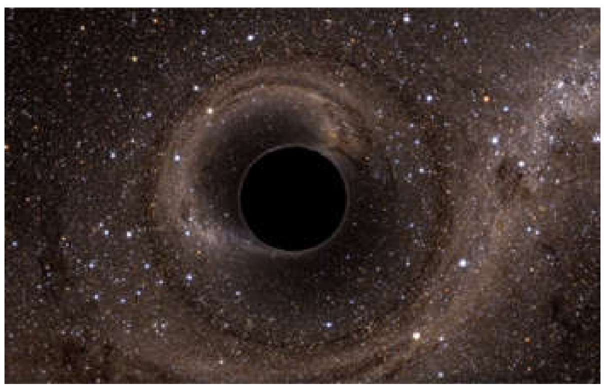


Illustration 31 : Gravitational Lensing

Gravitational lensing by the black hole's mass will distort the images of background stars. Therefore, the presence of an isolated black hole could still be deduced, if you are careful.

11 Black Hole Basics

In science fiction, plots often involve traveling astronomical distances. This is often achieved by using a type of warp drive, which circumvents the limit imposed by the speed of light, allowing faster than light travel. Warp drive is central to space travel and shows like 'Star Trek' putting it squarely into the realm of SF.

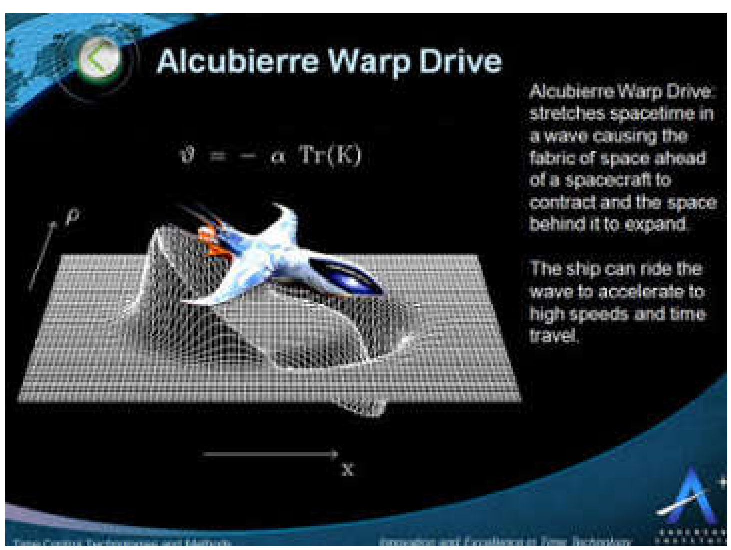


Illustration 32 : Alcubierre drive

However, there are some physicists who have proposed ideas for warp drive like phenomena. One such idea is the Alcubierre drive, named after a theoretical physicist Miguel Alcubierre, which could warp space-time with an exotic form of matter. Alternatively, many novels, movies, and TV-shows look for shortcuts through space called wormholes. Traversable wormholes have been used in many SF-stories, such as Carl Sagan's 'Contact' and 'Star Trek: Deep Space Nine.' These traversable wormholes are better than black holes for long distance space travel. However, unfortunately, they require large amounts of an exotic type of matter undiscovered to science. Unlike wormholes, there is strong evidence that black holes do exist in our Universe.

11.1 Categories

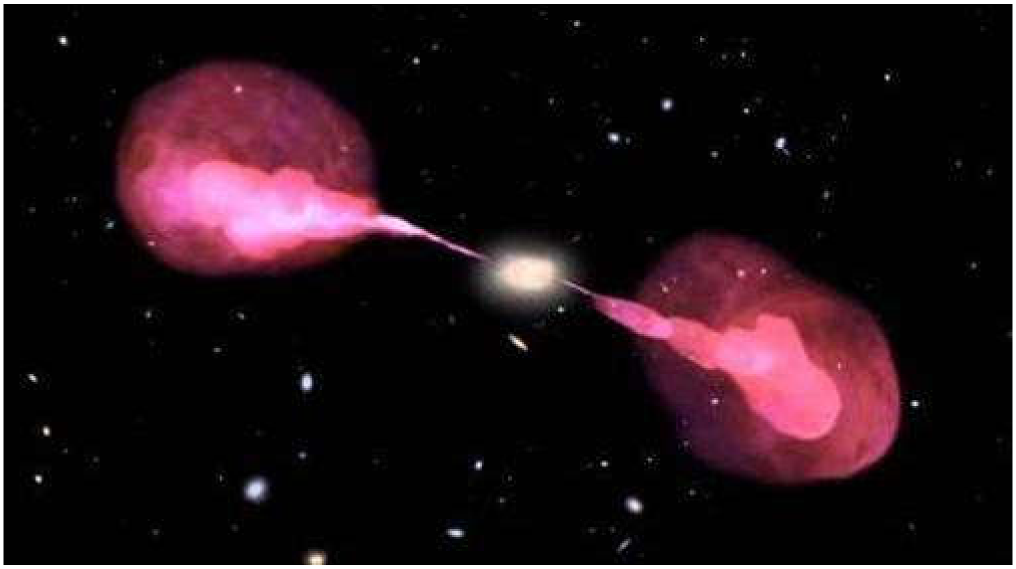


Illustration 33 : Supermassive black hole (Hercules A)

Black holes fall into several categories. Some black holes are formed by natural methods, such as the collapse of a high-mass star. Black holes with masses ranging from five times the Sun's mass to about 60 times the Sun's mass called stellar-mass black holes have been observed in our own galaxy and in nearby galaxies. We also see evidence of supermassive black holes with masses that are about 1,000,000 – 10,000,000 times more massive than the Sun at the centers of galaxies. It is also possible to form mini black holes artificially in experiments involving colliding proton and antiproton beams at the 'Large Hadron Collider.'

Today, astronomers are looking for evidence of black holes with masses that are intermediate between the stellar-mass black holes and the supermassive black holes. Nevertheless, no conclusive evidence for intermediate-mass black holes has been found so far.

To start us off in our journey to a black hole, we need to learn more about the destination. Specifically, let us begin our understanding of the life cycle of black holes by examining how they are formed in the first place. Through the birth, life, and death of massive stars, the progenitors of black holes.

Life And Death Of A Star

1 Introduction

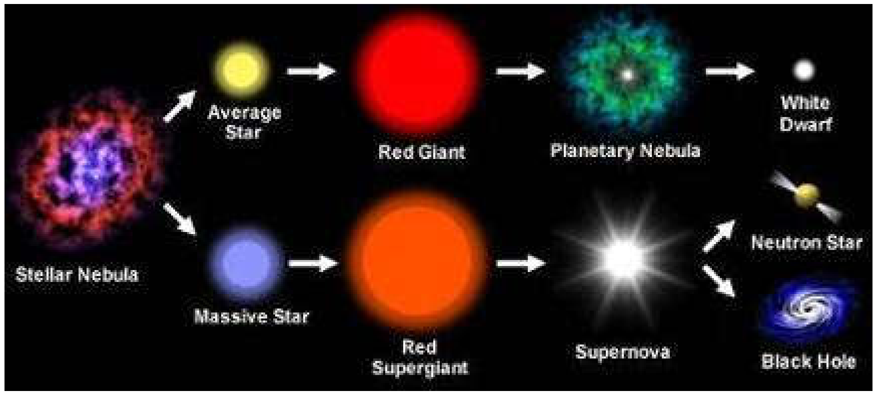


Illustration 34 : Life cycle of a star

Just as the natural cycle of life ends with death, so too does a star follow a familiar timeline. Birth, life, and eventually, yes, death. Let me reassure you right now, our Sun is in no danger of dying anytime soon, unless you consider 5,000,000,000 years soon. In the distant future, the Sun will die, but that is a good thing. The death of a star provides fertile material and fresh elements for the formation of new stars and star systems. In fact, our own solar system is thought to contain elements created by the death of several earlier star systems. All the elements heavier than H, He, and Li are produced in the fusion reactions of stars.

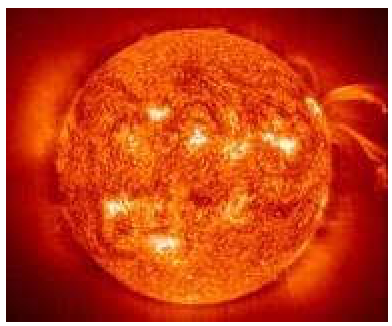


Illustration 35 : Our Sun

In order to understand how stars come to die, we first need to understand how they live. Most stars, like our Sun, live long and uneventful lives. Some astronomers might even call stars like our Sun boring. These stable, long-lived stars make great neighborhoods for planetary formation, and assuming a planet is at just the right distance from its host star, we might expect life to spring forth from a primordial ocean.

Illustration 36 : Supernova remnant W49B (Composite photo)

Some of the most interesting objects in the Universe are also produced in the final stages of a star's life. Strange remnants persist after the death of a star. Stars like our Sun produce white dwarf stars, and some high-mass stars result in the formation of neutron stars. Instead of a gentle death, high-mass stars use up their fuel very quickly and die in massive supernova explosions. If the star is massive enough, its death results in an even more exotic object. You guessed it, a black hole.

2 The Stellar Nursery

2.1 Star Formation

Illustration 37 : Cassiopeia supernova remnant

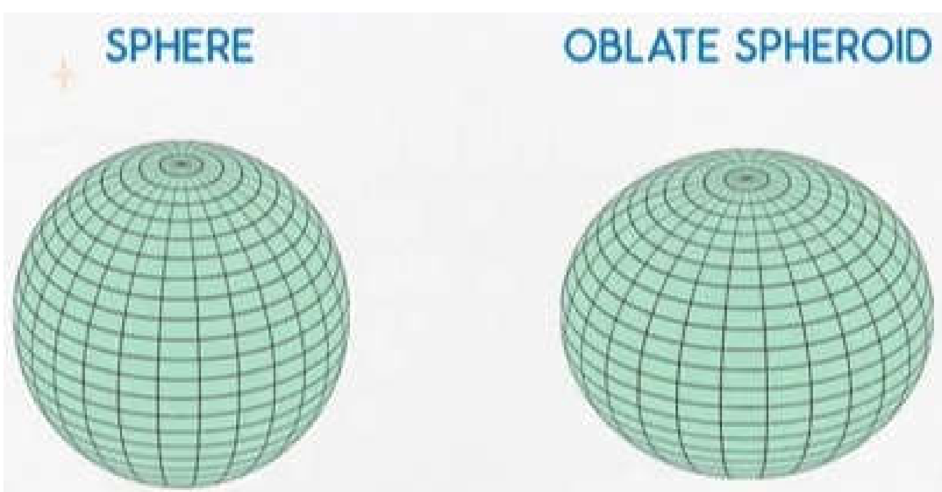
In order to understand the story of black holes fully, it is important that we start at the beginning. To know why black holes are formed, we must first understand why the objects, that form black holes, are formed. As stated in the introduction to this module, stellar-mass black holes are one of the two possible products of violent explosions of high-mass stars, which occur at the end of the star's life. These explosions, called 'Type-II' or 'Core-Collapse Supernovae,' occur in stars at least eight times more massive than our Sun.

When a massive star experiences a supernova event, the amount of energy released is approximately 10^{46} J. That is enough energy to last the Sun, at its present rate of energy output, 825,000,000,000 years. For reference, our solar system, along with our Sun, has existed for just 5,000,000,000 years. The Universe has existed for a mere 13,800,000,000 years. Clearly, that is a huge amount of energy.

If you were anything like me, right now you would have a ton of questions, starting with, how is it that some stars meet such violent ends? How do stars even form in the first place? Technically speaking, what is a star?

2.1.1 What Is A Star?

Simply put, a star is a big ball of gas. A ball of gas, which is gravitationally bound, dense, and hot enough to sustain a nuclear fusion reaction at its core. Our Sun is one such object. It, like all of the main sequence stars, produces energy by fusing H into He in its core.



Most stars are spherical or, if they happen to rotate quite quickly, we call then oblate spheroidal, because they are slightly squished. Now that we have a working definition of what a star is, let us move on to the next question.

2.1.2 How Do Stars Form?

Illustration 38 : Molecular cloud (Horsehead Nebula)

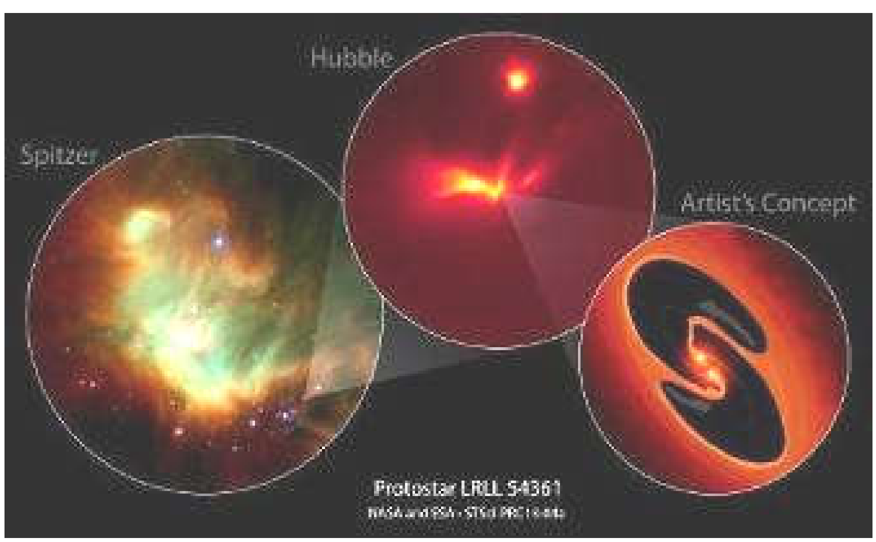
Stars form in clouds of gas and dust, which are particularly cold and dense, at least by interstellar standard. These regions are known as molecular clouds, because their temperatures are low enough to allow molecules to form. Molecular clouds are just one component of all the gas and dust in the space between the stars, known as the 'Interstellar Medium' or ISM. What distinguishes molecular clouds from other gas and dust in the ISM is the effect gravity has on them. Molecular clouds are cold, 10 – 30 K, and dense, several hundred $^{molecules}/_{qcm}$, meaning there are plenty of particles in close proximity to each other, at the same time, relatively little gas pressure. These two conditions are each very important for star formation, as they allow the inward force of gravity to overpower the outward force of the gas pressure, and initiate the collapse of the cloud.

As the cloud contracts, it releases gravitational potential energy. This energy is converted into thermal energy, which in turn, increases the pressure within the gas. Without some way of removing thermal energy, the gas pressure would build and eventually stop the contraction of the cloud all together, prior to the formation of the star. What is needed then is a way to get energy out. A way to get energy out, therefore, that gravity still has the advantage and contraction can continue.

2.2 Thermal Energy

Thermal energy manifests itself in the random motions and frequent collisions of molecules. Collisions between molecules and the gas can excite the molecules, allowing them to produce light that can escape the cloud. Therefore, without a buildup of thermal energy and gas pressure the cloud is free to continue contracting. However, as contraction continues, the central region within the cloud eventually becomes so dense that light emitted by molecules and by dust grains has a hard time escaping. More particles present in a given volume of the cloud means an increased likelihood of absorption of the light by other molecules, and subsequent conversion of that energy back into thermal energy.

2.3 Protostar



Over time, the clouds increasing density will result in nearly all of the radiation being trapped with in the central region of the cloud. When this radiation trapping occurs, pressure in the central region increases to a level that slows the rate of contraction. This is the formation of a protostar. When observed through telescopes, protostars look much the same as regular stars, in that they have similar luminosities and surface temperatures. The difference lies underneath, as protostars are not yet hot enough to sustain fusion reactions. In order to become hot enough to sustain fusion, protostars must gather more material and squish it. Material surrounding the protostar feeds down onto it, and at the same time, gravity continues to squish this proto-stellar material slowly into smaller and smaller regions.

As the protostar contracts and heats, the fusion rate increases. Moreover, the heat generated by these nuclear reactions provides a pressure force that slows the contraction caused by gravity. When the core temperature of the protostar reaches about 1,000,000 K, the winds generated at the protostars surface, blows the surrounding gas and dust away, ending the accretion phase. Now without its source of additional material, the protostar continues to slowly contract and heat until the core temperature reaches 10,000,000 K, at which point fusion becomes stable, and we have a star.

2.3.1 Hydrostatic Equilibrium

Fusion rates become stable because the forces in the interior of the star become balanced. Nuclear reaction rate are now high enough that they produce the necessary heat and pressure to prevent the star from collapsing further due to gravity. When the gravity and gas pressure forces are in balance, we call this state 'Hydrostatic Equilibrium.' The net force on material within the star is zero. The star can remain stable in this state for billions of years. Our Sun is currently about 5,000,000,000 years old and in a state of hydrostatic equilibrium. It will remain in this stable state for another 5,000,000,000 years.

It is time again for us to confess about a lie of omission we have been telling. Until this point, we have been considering a scenario star formation, which is not perfectly realistic. We have been considering a single cloud in isolation when in reality, individual sites of star formation are often influenced by other nearby sites of formation, and by nearby newborn stars. In truth, large molecular clouds fragment as they contract into several smaller cloud cores, and from these, one or more stars form. Often what we have is several neighboring sites, potentially each producing several stars.

Then there is the matter of those additional dynamical aspects we also forgot to mention. More than just two forces are present in molecular clouds as they contract. In addition to gravity and gas pressure, magnetic fields affect molecular clouds by slowing their contraction. Magnetic fields cause particles in a cloud to move in such a way that they exert a friction on each other, hindering motion within the gas and helping to prop up the cloud against gravity. Turbulence also plays an important role. Gas clumps moving relative to each other at large speeds act to shear the cloud apart, rather than facilitate the cloud's contraction.

In the later stages of star formation, materials surrounding the protostar will coalesce into a disc, and the protostar itself will eject material from the system, via large jets. Therefore, suffice to say, star formation is very complex, but star formation is also incredibly commonplace. Several stars finish forming in our galaxy every year. In addition, in total our galaxy contains roughly 100,000,000,000 stars. The key to our final question, how do some stars meet such violent ends, lies in the variety of stars, which result from the formation scenario.

3 Now That Is A Stellar Sequence!

3.1 Hertzsprung-Russell Diagram

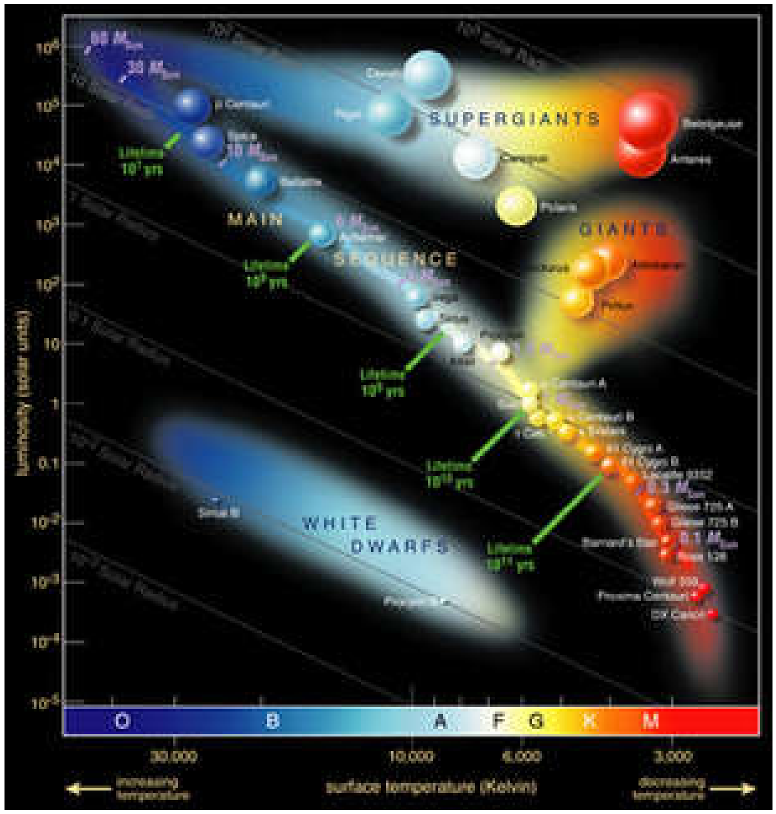


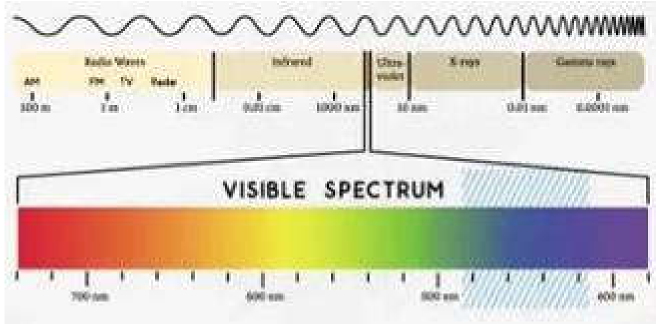
Illustration 39 : Hertzsprung-Russell diagram (HR-diagram)

A Hertzsprung-Russell diagram or HR-diagram is a tool common in astrophysics, used for the purpose of analyzing properties of populations of stars. It is a simple two-axis plot with luminosity increasing as you go up on the vertical axis, and temperature increasing as you move leftward on the horizontal axis. The temperature axis is flipped.

By observing a large number of stars and plotting each one as a point on one of these diagrams, we can begin to notice several patterns. Perhaps the most striking of which is what we call the main sequence. The main sequence of stars represented on the HR-diagram is a roughly diagonal swath of points, stretching from the low-luminosity, low-temperature region in the diagram to the high-luminosity, high-temperature region in the diagram. These are the stars, which originated from the formation scenario we described in the previous section.

Fusion rates have stabilized in their cores, and they are living out their adulthood in a state of hydrostatic equilibrium. The main sequence phase of a star's life, when considered relative to formation and to retirement, meaning prior to the death of a star, is the longest. As a note, we consider the death of a star to be any end state, such as the formation of a white dwarf, neutron star, or a black hole. We will see more about these in the coming sections. During the main sequence phase, a stable source of fuel is present in the form of H, which the star consumes converting it through fusion processes into He. Elderly stars, which have left the main sequence, source that energy not only from H, but from other elements as well.

For main sequence stars, there is a strong relationship between mass and luminosity. The more mass of the star, the brighter it is. The intense gravity of a massive star means its core will be denser, and as a result, hotter. This is important, because fusion rates’, meaning the rate at which energy is produced, is highly dependent on core temperature. Therefore, the more mass of a star, the more energy per unit time it produces, and as this energy leaves the core and, eventually, reaches the surface, we observe a greater luminosity, meaning a brighter star.



You will notice in taking the course that we often refer to stars by their color.

When we say color, what do we mean?

As we learned in a former module, electromagnetic radiation, or light, is a spectrum. Visible light is being just one portion of it. What we call blue is just an even smaller portion of the spectrum. Instead of simply calling it blue, we could define it in numbers, because as we know, light is characterized by its wavelength. Blue light has a wavelength of about 450 nm. Therefore, when we refer to a blue star, what we are saying is that much of its radiation is coming from this portion of the spectrum. When we say a star is bluer than another star, what we mean is that the bulk of the bluer star's radiation is coming from even shorter wavelength light. The same can be said of red and redder stars. As a redder star will have the bulk of its radiation in longer wavelength light.

Just like the filament of a light bulb, a star's light is produced by incandescent, or formally, blackbody radiation. Blackbody radiation is temperature dependent. The hotter a blackbody radiator is, the brighter it is. As the temperature of a blackbody emitter increases or decreases, it also changes color. This is why colder stars appear dim and red, and hotter stars are brighter and bluer.

The hottest stars in the sky, blue hyper-giants are upwards of 40,000 °C and can shine about 5,000,000 times brighter than our own Sun. We say that hotter stars are blue and the colder stars are red, but the reality with blackbody radiation is that every star produces at least a little bit of every color of the spectrum. When we say a star is blue, we are saying that the majority of its radiation is being produced in this portion of the spectrum.

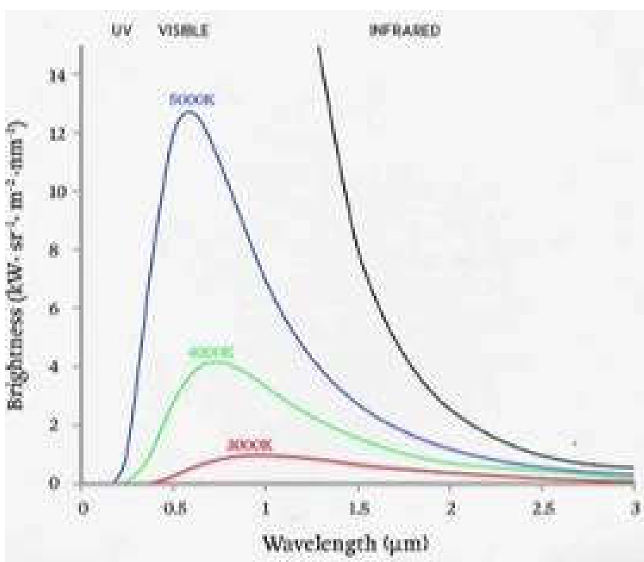


Illustration 40 : Different blackbody radiation

This majority exists because each blackbody emitter has a spectrum that is peaked, meaning there is a wavelength at which the star produces more light than at any other wavelength. This peak wavelength is directly related to the surface temperature of a star. The relationship is described by Wien's law, which takes the form of this equation.

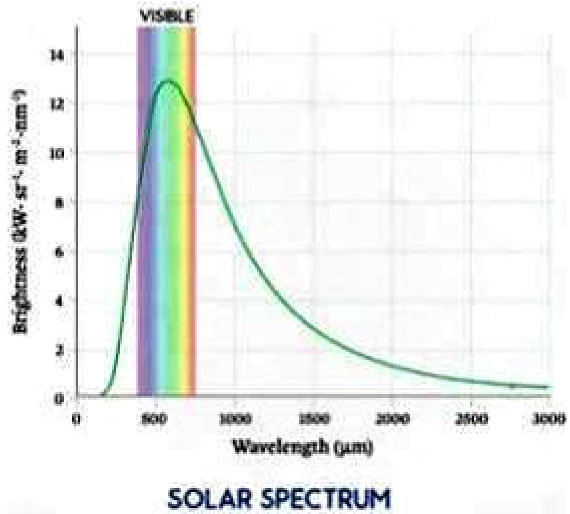
$$\lambda_{Peak} = 0.0029\left[\frac{mK}{T}\right]$$

Equation 9 : Wien's law

As we mentioned earlier, stars that are more massive are brighter, because they are more luminous as a result of having higher fusion rates. Despite having more material to burn, stars that are more massive live shorter. The more massive a main sequence star is, the quicker it exhausts the fuel in its core. Hot blue stars might live on the main sequence for 10,000,000 years, whereas a dim red star could live as long or longer than a trillion years, that is 100,000 times longer. This is why we like to personify stars. We would like to think of blue stars as rock stars that live fast and die young. Red stars live long and much more uneventful lives.

At midday, there is one star visible to our eyes, the Sun. At this point, you might be wondering where the Sun lies on an HR diagram.

How does it compare to other stars?



Well, the Sun happens to be average. It is not terribly hot or particularly cold. The Sun's spectrum peaks at a wavelength of about 500 nm, which is greenish. It appears whitish or yellowish to our eyes, because it is meeting a lot of light across the entire visible spectrum.

In terms of mass, the Sun lies fairly close to the lower end of what is possible for a main sequence star. At the high end, massive blue stars can be a couple of 100 times as massive as our Sun. At the low end, a red main sequence star can be as massive as a $^{1}/_{10}$ of our Sun.

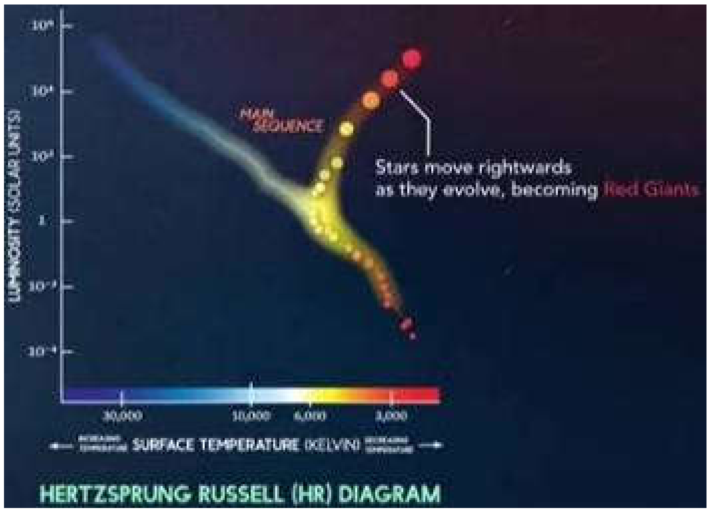
Illustration 41 : R136A1 (Rob)

The most massive star that is currently known lives at the edge of our galaxy. Scientists have given it the name R136A1, but we call it Rob. Rob has been measured at a whopping 256 solar masses. However, Rob has lost a great deal of material through fusion and winds, and it has thought that 20 % of its mass has been injected already. This would mean that at birth Rob was about 320 solar masses.

In terms of luminosity, the Sun is fairly average. Blue stars can be several million times as luminous as our Sun, and red stars can be much dimmer such that their luminosity is only a $^{1}/_{10,000}$ that of our Sun. One of the difficulties associated with constructing a HR-diagram of a population of stars is figuring out how bright the stars actually are versus how bright they look to us in the night sky.

Luminosity is a measure of how bright a star actually is. Apparent brightness is how bright a star will look to us. Apparent brightness is affected by distance, because the further away a star is, the dimmer it will appear to be, and we are not interested strictly in appearances. We want to be able to infer characteristics of the stars themselves. What we need to do then is measure a star's brightness knowing already how far it is from us, that way we can correct for its appearance meaning its distance, and compare it fairly to other stars.

Astronomers have spent hundreds of years constructing catalogs of objects with known properties, distances, and luminosities, therefore, that when we discover new objects, we can know much more about them. Being able to measure apparent brightness and distance accurately is very important. It means that we can construct an accurate HR-diagram, and that is crucial, because a HR-diagram is a tool, which allows us to learn even more, specifically, characteristics about an entire population of stars. For instance, we can use a HR-diagram to learn about the age of a population of stars. We can do this by determining the main sequence turnoff point.



As a star, exhaust the H-fuel supply in its core, its time on the main sequence ends. This is because the surface of the star cools as its core runs out of fuel, and therefore, it moves rightward on the HR-diagram away from that diagonal swath of stars.

Imagine we have a population of stars with a large variety of masses, all born at roughly the same time. Hot blue stars, if you remember, live fast, and die young. In other words, the stars in the high temperature, high luminosity region of the diagram will exhaust the fuel in their course first; they will move off the main sequence, and continue with the later stages of their lives.

Next to move off the main sequence will be stars, which are slightly less massive than those first stars, because, as you remember, the lower the mass of the star, the longer its main sequence lifetime. Over time, the main sequence will be slowly eaten away as less and less massive stars begin to move away. The point along the main sequence, where stars are departing, is called the main sequence turnoff point. We can measure the properties of the stars at this point, and because we know how long every type of main sequence star typically lives, we can learn the age of the entire population of stars.

4 Energy Production In Stars

4.1 Fusion

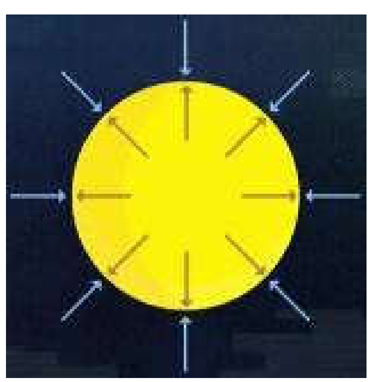


Illustration 42 : Hydrostatic equilibrium

Stars are powered by a nuclear reaction at their core. Fusion is the source of a star's power, which keeps them hot, and allows them to produce light. Fusion also keeps a star from collapsing. Since the atoms at the core of the Sun are heated to incredible temperatures, their motion and collisions create a gas pressure that pushes material outward counteracting the gravitational forces that pull material in. This balance of outward gas pressure and inward gravitational forces keep a star in hydrostatic equilibrium.

Chemical reactions are just one of the ways that energy can be released as heat. For millennia, humans have harnessed the energy of chemical reactions with the power of the campfire. Fire is a reaction that breaks the chemical bonds in the materials like wood releasing excess energy as light and heat. However, the Sun requires much more powerful source of energy to continuously burn for its 10-billion-year lifetime. If the Sun were made of wood and burned by conventional combustion, it would only last a few thousand years.

Nuclear reactions are about a million times more energetic than chemical reactions; therefore, they are a much better source of energy for stars to use. In fact, researchers here on Earth are trying to replicate the conditions at the center of the Sun; therefore, that humanity can enjoy the abundant energy of nuclear fusion.

4.2 Structure Of An Atom

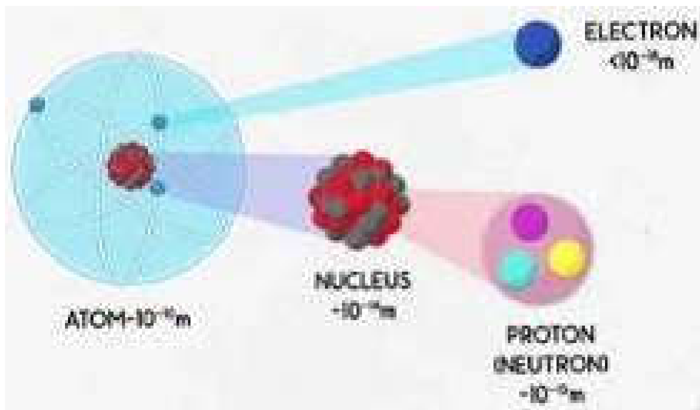


Illustration 43 : Structure of an Atom

In order to understand the difference between chemical and nuclear reactions, we need to understand the structure of an atom, its nucleus, and some of the subatomic particles like protons, and neutrons. All atoms consist of a small dense nucleus, and a cloud of electrons bound by electromagnetic forces. Within the nucleus itself, there are two major components, protons, and neutrons. Both protons and neutrons are made up of quarks, protons in such a way that they end up with a positive charge, and neutrons, which are neutrally charged. Both protons and neutrons weigh about the same, but the neutron is slightly heavier. Since the proton has a positive charge and like charges repel, all protons within the nucleus will repel one another.

4.3 Nature Forces

Why do nucleuses not explode due to this repulsion?

Gravity and electromagnetism are only two of the four forces that exist in nature. The strong nuclear force is the third and is responsible for tightly binding protons and neutrons together in the nucleus. The strong nuclear force only works over very short distances, too short for us to experience in everyday life. However, it is so strong that it can overcome the electrostatic repulsion between protons within the nucleus.

The fourth force of nature is called the weak nuclear force. It allows protons and neutrons to transform into one another. These types of transformations are the evidence that we have that protons and neutrons are not themselves fundamental particles. They are composed of even smaller particles called quarks and gluons. On the other hand, electrons are fundamental particles. Scientists do not think we can take electrons apart into any smaller pieces. With a mass that is 2,000 times smaller than that of a proton, electrons are the zippy particles that have a negative electric charge.

4.4 Antimatter

Additionally, all particles in nature have an antiparticle kind of like an evil counterpart. Antiparticles share the same mass as their normal particle partners, but they have the opposite charge. For example, the antiparticle version of an electron is called a positron. When electrons and positrons come close to each other, they are attracted together by their opposite charges, and they destroy each other in an explosion of pure energy.

4.5 Neutrinos

Finally, the tiniest particles involved in nuclear reactions are neutrinos, a name that means little neutral ones. Neutrinos have a very tiny mass, so small that it is difficult to measure. We call neutrinos weakly interacting particles since they do not have an electric charge, nor do they feel the strong nuclear force. The only forces that affect neutrinos are gravity, like all particles, and the weak nuclear force. This makes them very hard to detect since they emit no light, and can pass through many thousands of kilometers of a dense material like Pb without colliding with any of the other particles. That is our particle physics recap.

4.6 Hydrogen

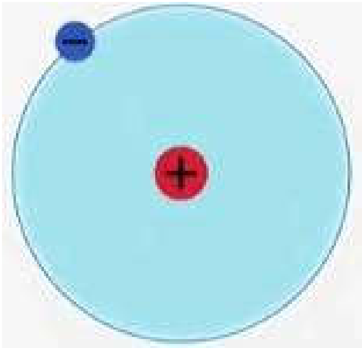


Illustration 44 : Bohr model of an H-atom

Let us look at a practical example. The simplest atom is H. Most H-atoms contain only one proton in the nucleus with a single electron orbiting far from the atom's core. In the above illustration, the orbitals are shown as circular planetary-like orbits. However, that is not at all a correct illustration of the atom. On small scales, the behavior of atoms is governed by quantum physics. Therefore, a better illustration of the H-atom would be smeared out into probability clouds.

A scale model of H would not look like this either. The distance between the electron and the proton is about 100,000 times wider than the radius of the proton itself. If you wanted to make a scale model of H, the distance between the electron and the proton should be 100,000 times larger than the radius of the proton itself. This is often why you hear the claim that atoms are mostly empty space.

For example, if this pebble were the size of a proton,

the electron would have to be more than 1 km away.

The proton, neutron, and electron are elementary particles. The strong and weak nuclear forces govern their behavior at very high energies. However, in regular everyday life, we interact with matter through the electromagnetic force that governs chemistry.

A typical chemical reaction like H and O reacting to form H_2O is a process that breaks and forms chemical bonds between atoms. These chemical bonds are a complicated function of how the electrons are shared between different types of atoms, different elements.

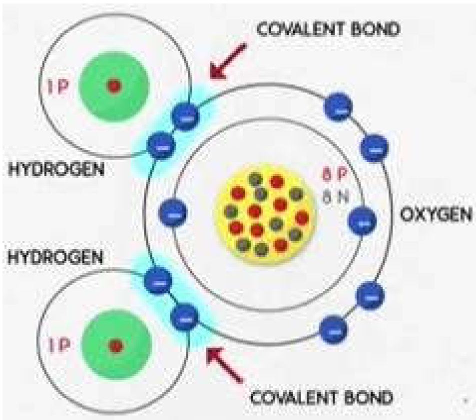


Illustration 45 : Bohr model of water

For example, if two H-atoms come together with an O-atom, they can form a molecule of water, H_2O, by sharing electrons in covalent bonds. The production of water is an example of an exothermic reaction, which means that the reaction releases heat. Chemical reactions interact through the electromagnetic force.

What kind of reactions are nuclear reactions then?

Nuclear reactions only take place between the protons and neutrons within the nucleus of an atom. Since protons are charged positive, they repel one another, but they are held together by the strong nuclear force between the protons and the neutrons. By adding or subtracting protons and neutrons, new atomic nuclei can be created, but this takes a tremendous amount of energy. In a nuclear reaction, protons and neutrons can also be converted into one another, and new atomic nuclei can be created.

4.7 Fusion And Fission

4.7.1 Fission

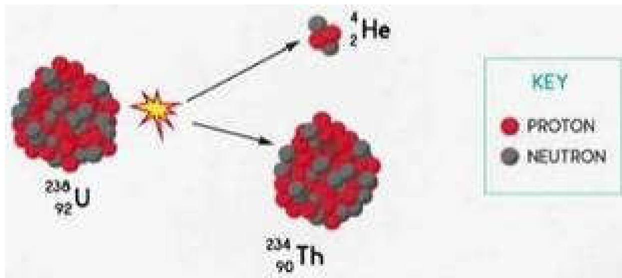


Illustration 46 : α-decay of a ^{238}U-nucleus

There are two types of nuclear reactions: fusion and fission reactions. For very large atoms like ^{238}U, the proton-to-proton repulsion is so strong that across the width of the nucleus, there is enough electrostatic force to overcome the strong nuclear binding energy. ^{238}U-nuclei split on a timescale of 4,400,000,000 years, and when they do, they produce a Th-atom through the emission of an α-particle.

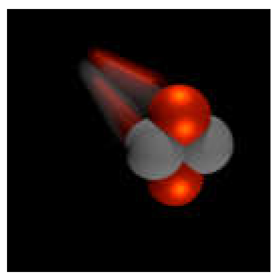


Illustration 47 : α-particle

α-particles are just naked He-nuclei with no electrons to cover them up.

When large atoms split into smaller ones, we call the process nuclear fission. I remember that fission breaks nuclei apart, using the phrase 'fish n' chips' or fission chips. When I eat fission chips, I break them into smaller pieces. Current nuclear reactor technologies here on Earth use fission reactions to release energy. NASA is even investigating nuclear fission for future space engines.

4.7.2 Fusion

You can also combine nuclei together, the reverse of fission in a process called nuclear fusion. The word fusion means, the process of joining two or more things together to form a single entity. In a nuclear fusion reaction, two or more small nuclei are joined together to form a bigger nucleus. Just like jazz fusion, as a musical combination of jazz, funk, rock, and blues, so too can protons and neutrons fusion together to form a bigger nuclei.

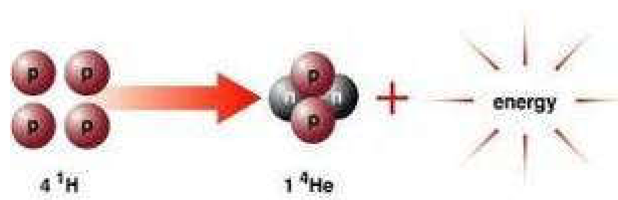


Illustration 48 : H-Fusion

Both fusion and fission reactions can release energy, but it depends on the details of the reaction. In the Sun, fusion reactions combine four H-nuclei together to produce one He-nucleus, plus some energy. This process produces most of the Sun's energy. The most important nuclear reaction taking place in the core of the Sun is the fusion of H into He. This reaction releases nuclear energy, the energy that powers the Sun. Rather than a cartoon; let us approach H-fusion with more scientific notation.

$$4\mathrm{H} \rightarrow \mathrm{He} + 2\,\mathrm{e}^{+} + 2\,\nu + \gamma$$

Formula 1 : H-Fusion

The reaction takes place in a few steps. Four H-atoms produce one He-nucleus, plus two positrons, plus two neutrinos, plus one γ-ray photon. A positron is denoted as e^+ and is the antimatter partner of the electron. A neutrino is denoted with the Greek letter ν. The Greek letter γ is used to denote light. The H-fusion reaction is sometimes called the p-p chain since it involves protons.

4.8 Mass Defect

We can add up the mass of the four original H-nuclei, and compare it with the mass of the He-nucleus that is produced. We find that the He-nucleus weighs less than the sum of the four original H-atoms. Some mass is lost during the fusion reaction. The mass is not really lost; it has been transformed into thermal energy as described by Einstein's famous equation:

$$E = mc^2$$

In this equation, m is the mass lost in the fusion process, c is the speed of light, and E is the energy that is released by the reaction, which now heats up the Sun's core. The term c^2 is such a large number that even tiny masses can be consumed in reactions and amplified into huge energies. The difference in mass before and after a nuclear reaction takes place is called the mass defect. The larger the mass defect, the larger the amount of energy that will be released in the reaction.

4.9 Binding Energy

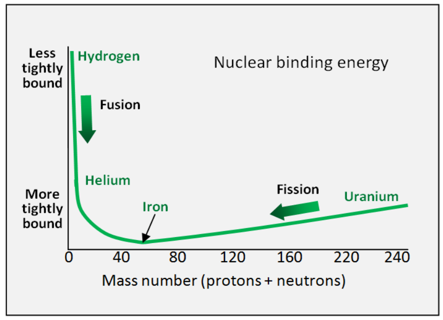
$$\mathrm{BindingEnergy} = \left(Zm_p + Nm_n - m_{nucleus}\right) * c^2$$

Equation 10 : Binding Energy of a Nucleus

Another related quantity, is the binding energy of a nucleus. Any nucleus is made up of N neutrons and Z protons, whereas N and Z depend on the specific element. The binding energy is defined by adding the mass of all protons and neutrons, subtracting the mass of the nucleus, and then multiplying by c^2. This binding energy is the amount of energy that you can extract from a reaction if you bind all the protons and neutrons into a nucleus. Alternatively, if you want to rip apart the nucleus, the binding energy is the amount of energy that you would have to apply. In order for the fusion of H into He to take place, the positively charged protons have to come close to each other before they can fuse. However, positive particles repel one another. We need to give the proton some extra energy; therefore, they can get close enough that the strong nuclear force can glue them together.

This requires that the conditions in the Sun's core be very hot and dense. Only the inner 25 % of the Sun is hot and dense enough for nuclear fusion to take place. The center of the Sun is about 15,000,000 K. The outer parts of the Sun are too cool for nuclear reactions to take place. Since H is slowly being transformed into He in the core of a star, this means the star is slowly using up its fuel. Eventually, the core will be depleted of H. The end of the hydrogen fusion in the core of a star, signals the end of the main sequence stage of that star's life.

Nuclear fusion of He into C also releases energy. Therefore, this and other nuclear reactions that build up higher mass elements can take place in stars. However, the heaviest element that can be formed by the nuclear fusion process Fe iron. Fe is a special element. In any nucleus, there is interplay between the strong nuclear force, which has a small distance range and glues protons and neutrons together, and the electrostatic force, which is long range that wants to keep protons apart. Since the strong force is only strong at small distances, there is a special element, Fe, which has the most tightly bound nucleus.



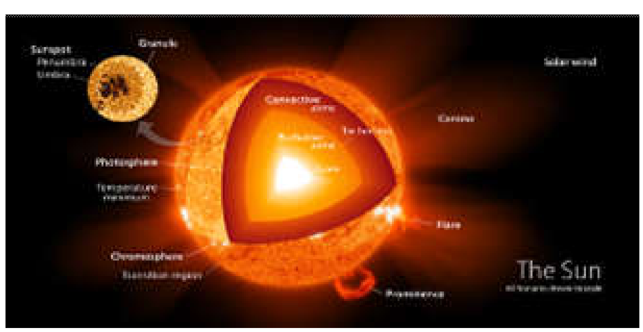
This graph shows the binding energy of the nucleus of different elements. Energy is released in reactions that transform light elements into heavier elements, corresponding to downwards on this graph. Nuclear fusion releases energy when elements with masses as large as Fe are formed. Similarly, nuclear fission can release energy as high-mass elements are split into smaller ones until they are as small as Fe. However, we cannot gain energy from Fe by either breaking it apart or smashing two Fe-nuclei together. As no energy can be gained, a star that has accumulated Fe in the process of nuclear fusion has nothing left for the star to feed on. Fe cannot be used as fuel, and the star must die. This is sometimes called the Fe-catastrophe, which leads to the death of a star.

5 Energy Loss In Stars

Illustration 49 : Sudbury neutrino observatory

At the core of all stars, there is a glowing nuclear furnace. We can be sure of this, because we can measure how many neutrinos are streaming out of the Sun with experiments like the 'Sudbury Neutrino Observatory.' This property of neutrinos, that they can pass through the core of the star virtually unimpeded, it is because neutrinos are weakly interactive particles, which is to say that they do not interact with electromagnetic forces like particles or photons do interact electromagnetically, and thus they have a very difficult time leaving the core of a star.

5.1 Inner Regions Of Our Sun



Let us carve into our own Sun and examine how the energy produced at the core is radiated away as the light that we see here on Earth. The innermost region of the Sun extending from the center to about one quarter of the radius of the Sun is the region where nuclear fusion takes place. This is aptly named the thermonuclear energy core. In this innermost region, the temperature, pressure, and density are extremely high, suitable for elements to combine in the process of fusion. The temperature has been estimated to be $1.55 * 10^7$ K, roughly 15,000,000 °C. The density of the material is nearly 14 times the density of Pb, and the pressure is almost a billion times the atmospheric pressure here on Earth. Needless to say, you would not want to go there, but if you did find yourself there, you would want to escape pretty fast.

5.2 Energy Transfer In Our Sun

In order for energy to escape from this region, it needs to be carried away by one of three processes.

- **Conduction**
- **Convection**
- **Radiation**

5.2.1 Radiation

Conduction, which is the propagation of heat through a solid, is inefficient in the Sun because, well, the Sun is not a solid. In this centermost region, extending to about ¾ of the diameter of the Sun, energy is carried away by the processes of radiation, the motion of photons. Extending outward from the thermonuclear energy core, the radiative zone is a region of the Sun where photons dominate the energy flow towards the surface of the Sun. You think that light, travelling at just over a billion $^{km}/_{h}$, would not take long to escape from the core of the Sun. Moreover, indeed, if there were nothing impeding the progress of photons inside the Sun, they would take about 2.3 seconds to cross the Sun's nearly 700,000 km radius.

However, photons are impeded by the materials of the Sun. Instead of 2.3 seconds, photons take an average of 170,000 years to escape into space. That is right; the energy we observe in the form of sunlight has been working its way to the surface of the Sun for hundreds of thousands of years. Within the first ¾ of the diameter of the Sun, photons bounce around on very short paths, randomly walking their way towards the surface. Each step taken by a photon amounts to about 1 cm, and the energy must be carried nearly 700,000 km. Just like the balls in a toy version of a rain stick, photons jostle through the materials of the Sun, colliding and careening their way to the surface. Not every step will be directed towards the surface of the Sun, though. Nevertheless, photons will preferentially migrate towards the surface due to the temperature grading. If you consider that a rain stick has a gravity radiant, instead of a temperature one, it is not a bad analogy for the motion of photons within the Sun.

Have a look at the math. If you took a 1 cm step every second, it would take you over 2,000 years to walk 700,000 km. However, that is assuming that you would walk in a straight line. If you stumbled around randomly, say, after getting off a dizzying rollercoaster, it would take you quite a bit longer to get where you want to go. Eventually, the energy from the core of the Sun stumbles its way to the surface.

5.2.2 Convection

From the centermost thermonuclear energy core, encompassing the first ¼ of the Sun's radius, through the radiative zone, from ¼ to about $^{7}/_{10}$ of the Sun, photons encounter the convective zone, the outermost layer of the Sun's surface. As you move outward, the average temperature of the Sun drops, and at the boundary of the convective zone, it is cool enough for electrons and protons to join into H-atoms, which happen to be very good at absorbing photons. Radiative energy transfer is no longer the dominant process and convection takes over.

5.2.3 Conduction

Illustration 50 : Lava lamp

Atoms heated at the bottom of the convective zone become buoyant, and the mass of the hot atoms and plasma rise to the surface like bubbles in a lava lamp. Cooler gas at the surface of the Sun sinks down to replace the hot gas that is rising, and the process repeats. Once the hot gas reaches the Sun's surface, energy stored in the heat of the gas is emitted as black body photons, which can then travel across the vast distances of space, virtually unimpeded. Now that there are finally some photons escaping the Sun, let us put on our safe solar filtering glasses and have a look.

6 The Sun’s Light And Life On Earth

Do not look directly at the Sun. The Sun is bright, and our squishy, liquid-filled human eyes have evolved for use in an average solar or radiance environment. That is a mouthful. However, the lesson is simple. Do not look directly at the Sun even using sunglasses. Doing so can permanently damage your eyes and your ability to see. In extreme cases, you may become permanently blind.

6.1 Safe Ways To Look At The Sun

Illustration 51 : Solar eclipse sunglasses

There are safe ways to look at the Sun. Either by reducing the total light that we observe with our eyes, or by narrowing the spectrum of interests into a short range of colors. Common light reducing tools are the number 14 welder’s glass, or an astronomy-specific pair of solar sunglasses like this. Now, that we are finally equipped to look at the Sun, let us go ahead and have a look.

6.2 The Sun’s Surface

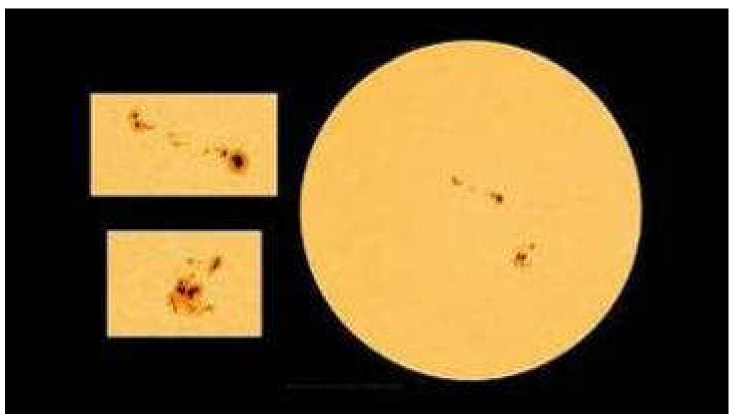


Illustration 52 : Sun's surface (Photosphere) with Sun spots

Wow! The Sun's surface, which is called the photosphere, is a roiling inferno of activity. Bright patches model the surface separated into small cells by darker boundaries. Once in a while, you encounter a very dark patch, a Sunspot.

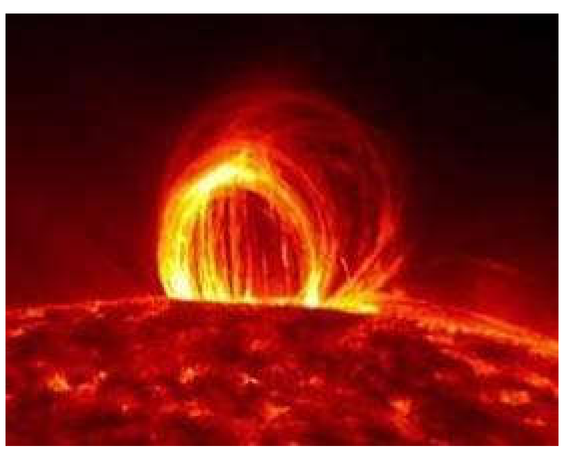


Illustration 53 : Hot gas following the magnetic lines

If you look closely, you can also see hot gases above the Sun's surface following magnetic field lines.

Every detail we see on the surface of the Sun is the result of the thermonuclear reaction at the core. The photons that eventually escape from the surface of the Sun are not the same ones that began the journey in the nuclear furnace at the stellar interior. Although the energy was produced by fusion, that energy went through several stages in its 100,000-year journey. The most notable was the journey through the convective zone, where our photons energy was locked away in the vibrations of the H- and He-gases as they floated to the surface.

Once exposed to the vast vacuum of space, the heat energy contained within those vibrations can now escape freely as photons. Since these photons originate from hot dense gas, they are mostly the result of blackbody radiation. Some sprinklings of atomic H-emission and -absorption are present in the Sun’s spectrum. However, the dominant component of the spectrum is the result of the Sun's surface temperature.

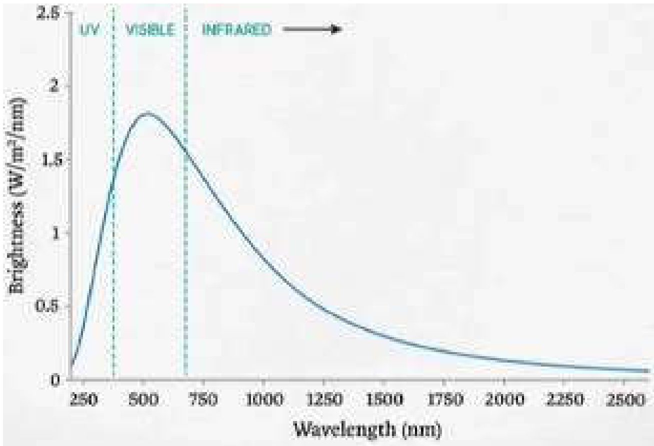


Illustration 54 : Solar radiation spectrum

Since we can measure what the peak wavelength of the Sun's blackbody emission is, we can use Wien's law to calculate the average surface temperature of the Sun as well. Since the Sun's peak wavelength is about 500 nm, which is to say a yellow-greenish color, we will plug that number into Wien's law in order to calculate the surface temperature.

$$T_K = \frac{2.898 * 10^{-3}\, mK}{\lambda_{peak}}$$

Equation 11 : Wien's law

Therefore, the Sun's surface temperature is 5,796 K. The fact that the Sun does not look green, when in fact it has a peak emission in the wavelength of green, is due to the fact that the Sun also emits a lot of red and blue light, and when you combine red, green, and blue light, we observe it as a white light.

Illustration 55 : Solar granules

What about this strange pattern on the surface of the Sun? What causes this pattern to emerge?

These are called solar granules, and are the result of the convection in the photosphere. Hot gases rising from the stellar interior are visible as bright patches of yellow.

What happens to them once they are at the surface?

At the surface, these gases emit light, and in doing so, cool down. The cooler gases are now denser, and therefore, less buoyant. They begin descending in the zones at the boundaries of the hotspots. These cooler gases are visible as the grain-like boundaries on the Sun's surface, and this is where the cool gases begin their descent.

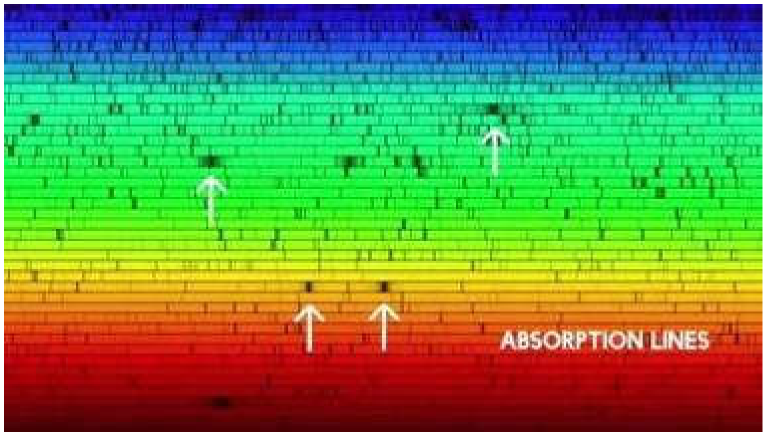
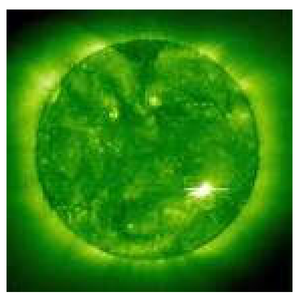


Illustration 56 : Solar absorption spectrum

The Sun's photosphere is a layer of gas that becomes cooler in the outermost layers. This images of the Sun's visible light shows all the colors of the rainbow and corresponds to blackbody emission from the lowest region of the photosphere.

As the light travels outward through the photosphere, some of the light with special colors is absorbed by the cooler H-gas and other elements present in the atmosphere. When the light is absorbed at these colors, we see black lines instead of that color. We call this an absorption spectrum. The Sun does not just produce good old-fashioned visible light. Wien's law tells us that it also produces high-energy UV radiation and X-rays too.



These images come from NASA's 'Solar and Heliospheric Observatory,' called SOHO for short, and show the Sun at wavelengths that our eyes cannot see. This image for example, was taken with a peak wavelength in the ultraviolet, or at 19.5 nm. Revealing even more of the stellar atmosphere that was not visible to the naked eye. Not only that, but in the UV, there is much more contrast. Therefore, activity in and above the photosphere is much more apparent.

6.3 Chromosphere And Corona

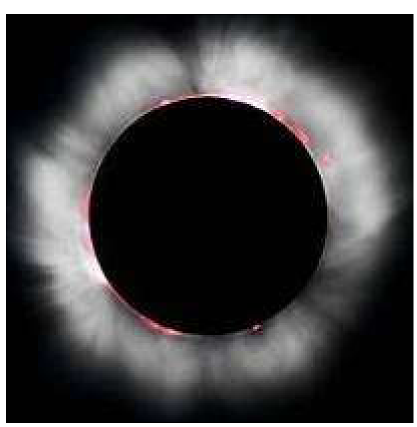


Illustration 57 : Corona of our Sun

The outermost regions of the Sun's atmosphere are called the chromosphere and the corona. The corona is much hotter than the Sun's surface, which scientists think is a result of the tremendous energy contained within the magnetic fields that are generated by the Sun.

6.4 Solar Energy

The energy produced at the core of the Sun is the same energy that nearly all of life depends on. From the water cycle to the web of life, the majority of the energy required to sustain all plant and animal life on Earth, comes from the Sun. The energy that we release when we burn hydrocarbon-based fuels can be traced back through geological time to a moment when an ancient plant absorbed light from the Sun. Which eventually contributed to coal seams and oil wells where we derive the fuel for our modern life. This is contrasted by modern renewable fuel sources like solar energy that convert direct sunlight into electricity. In a sense, almost all energy sources can be considered solar energy.

6.5 Habitable Zone

We happened to be in a relatively stable energy environment around the Sun. If Earth were closer to the Sun, like Mercury and Venus, it would be much too hot for life to exist, as we know it. Similarly, if Earth were farther away from the Sun, like Mars's orbital radius, it would be much too cold for most of life to survive. Asking where a planet can have liquid water, or more importantly, the conditions required to sustain life, is a fundamental question that many scientists have asked throughout human history. Astrobiologists, people who study both astronomy and biology, call this region the habitable zone. Generally speaking, the habitable zone is a region surrounding a star where a planetary body like Earth would be able to support liquid water. There is some flexibility in this definition since it would include frigid planets where the maximum temperature is just above the freezing point of water, and intensely hot planets whose minimum temperature dips just below the boiling point of water. Let us look at our own solar system and see where we would draw the boundaries of the habitable zone.

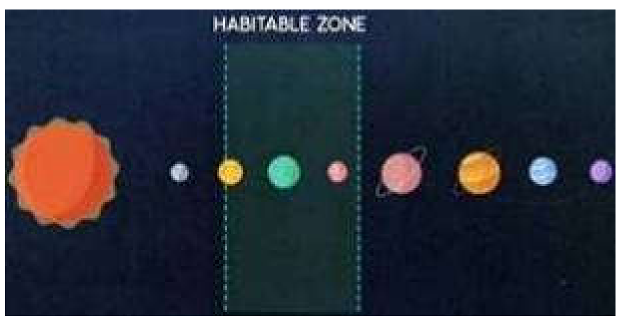


Illustration 58 : Habitable Zone of the Solar System

Scientists believe that our own solar systems habitable zone extends as close to the Sun as Venus at just under ¾ of an AU, to as far as twice Mars's orbit or twice 1.5 AU. Arguments vary regarding what we consider normal life, since we have examples here on Earth of extremophiles that can live at extreme temperatures. Therefore, we will just have to leave the boundaries of the habitable zone as what they are, estimates.

What if Earth were in orbit around a different type of star instead of the G-type star we currently orbit?

Illustration 59 : Habitable Zone of an M-Type Star

M-type stars, like our nearest stellar neighbor Proxima Centauri, are cooler, red dwarf cousins of our own Sun. Since they have a lower surface temperature, the habitable zone around has to contract to smaller distances. If Earth were stayed at the same distance from an M-type star like this, it would quickly turn into an icy snowball at the edge of the new habitable zone.

On the other hand, if the Sun were suddenly replaced with a more massive, and, therefore, higher temperature star, like a blue blazing B-type star Bellatrix, the habitable zone would move outward in the solar system leaving Earth a burnt crisp.

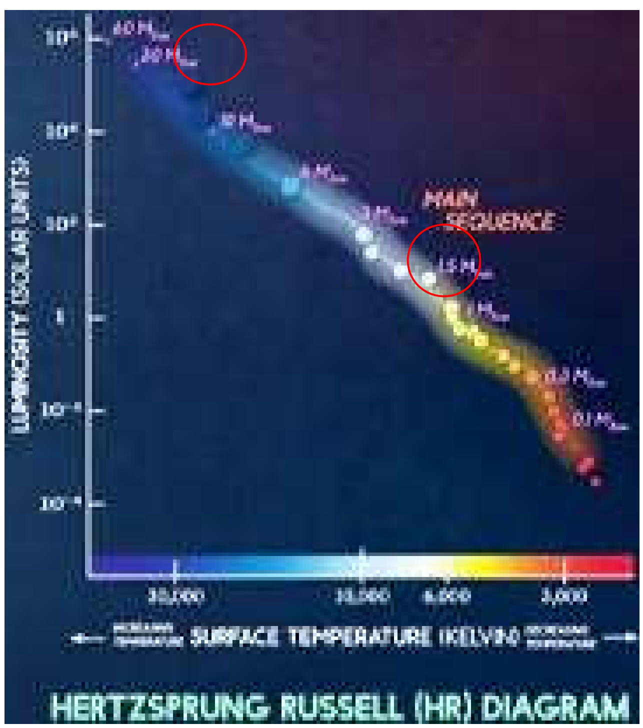
Similar effects can happen as stars age as well. As stars move off the main sequence, they enter a series of stages where luminosity and radius tend to increase. We will see more about this in the next section.

7 End Of A Star's Life

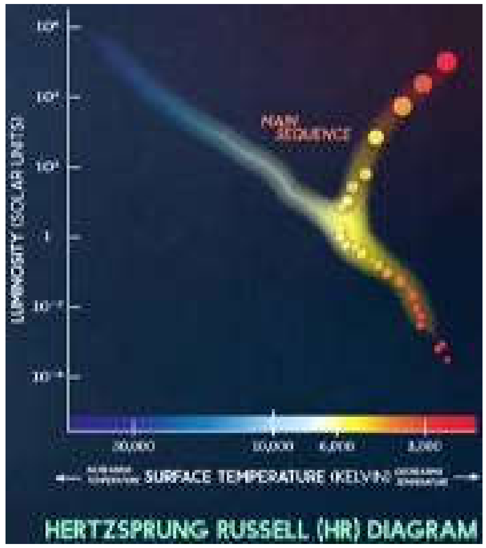
Within this module, we have looked at the birth and life of stars. We have explored the stellar nurseries, and discovered that stars, just like humans, walk different paths. Yes, we all eat, sleep, and explore life, or in the case of a star, burn fuel, and shine bright. However, just as there are different paces of life for us humans, therefore, stars too can live and die in many different ways.

Now that we know the basics, let us explore the life of rock stars and that of average joeys, in the stellar sense that is. Let us see how different stars move towards the end of their lives. Here we will discover that the life and subsequent death of a star are determined at birth by the stars mass.

How can this be the case?



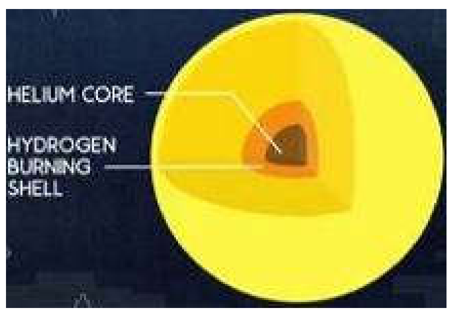
The story of a star's death begins at the point at which it leaves the safety and security of the main sequence. The main sequence is the long main track observed in the HR-diagram. We have learned that stars seen in the upper left of this track burn hot, blue, and are massive, weighing 10 - 100 times the mass of our Sun, or possibly more. Stars at the lower right of the track are cool by stellar standards. They are red, and may only contain a $^{1}/_{10}$ of the mass of our Sun. We have also learned that blue stars tend to be called high-mass, while stars like our Sun and smaller are often called low mass stars.



When a star leaves the main sequence of the HR-diagram, the star is seen to move towards the right of this plot. This movement is the result of the star becoming redder.

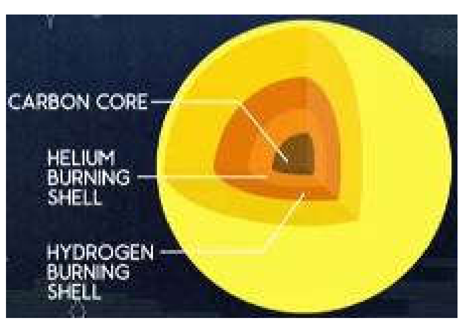
What does this change in color represent? What changes in the star's interior are powering the shift? In addition, what happens in the time between the departure from the main sequence, and the star's demise?

This is what we are about to explore.



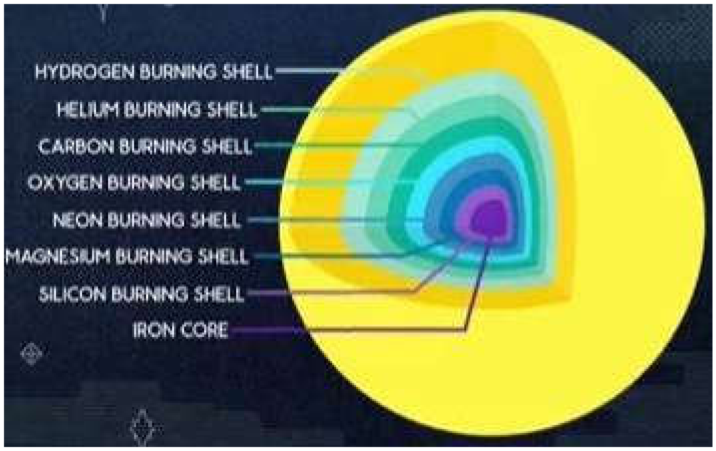
When a star's core runs out of H-fuel, the core can no longer sustain the outward radiation force that balances the force of gravity, which is pulling everything inwards. Therefore, the star will no longer be in hydrostatic equilibrium. This loss of radiation pressure results in the stars core collapsing. The collapse of the core in turn causes the temperature of the interior to increase.

When a star burning primarily H suffers from such a collapse, it will contract until the core reaches about 100,000,000 °C. At that temperature, the star can begin to burn He in its core. He will become the main source of energy for the star at this point, as it fuses to create C and other trace elements. However, if we look just outside the HE-core, we can see that the core is surrounded by a shell of H that is also burning. This H-shell is slowly consuming more material as it moves outward through the star. As the He burns hotter than its predecessor does, the H-core, it burns more rapidly; therefore, this phase of the star's life is shorter.



Once the He-core is exhausted, the core will once again collapse. As it collapses, the temperature will once again increase. If the collapse leads to a temperature of 600,000,000 °C, the star is able to burn C. Such a core would be surrounded by both He- and H-shells.

Once the C burning is complete, the cycle can again repeat, leading to Ne, O, and even Si burning, with the core becoming heavier and heavier.



As each layer is hotter than the last, the star burns through the core more rapidly. For example, a star could take billions of years to burn through its H, whilst it may only take hundreds of years to feed on a C-core. By the time we reach Si, it is possible for a star to consume its core in about a day.

The multiple layers of a star seen here have led to these stars sometimes gaining the nickname of onion stars, as onions have layers, just like ogres, or cakes, or parfaits. Yes, they have layers, but it all stops with Fe.

When learning about fusion and fission we discovered that the most tightly bound atom is Fe, and that no more energy can be gained by either breaking Fe apart or by smashing two Fe-nuclei together. As a result, there is no fuel left for the star to burn through. Fusion in the core must stop, and the star will die. We will explore more of the death of stars in the next two lessons.

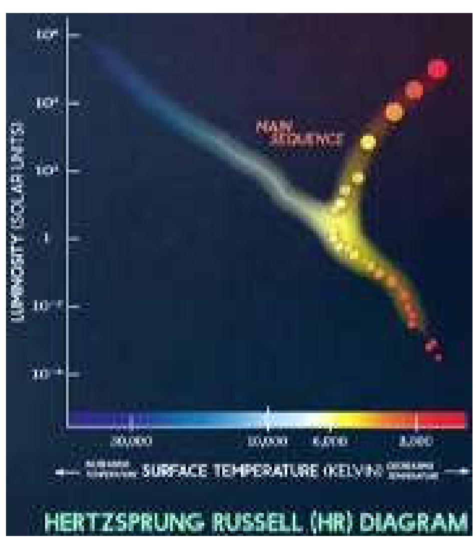
So far we have been looking at what is going on inside the star, but what effect does that have on the outside of the star? Rather, what effect does that have on what we can see?

When stars run out of the current fuel in their core, we discovered that the cores collapse. This continues until the star is able to burn a new type of fuel. For example, when a star initially runs out of H, it will collapse until the He fires begin to burn.

What effect does this have on the envelope of the star?

The envelope is the outer H-rich region of the star, which is not involved in nuclear fusion. It is the outer layer of the star. Well, as the core collapses the energy generated by this collapse drives the diffuse envelope outwards; and therefore, the star expands. As it becomes less dense, it cools, and therefore, it reddens. This means that we would see the star appear to grow in size while becoming redder.

7.1 Star's Turnoff



If we return to the HR-diagram, we will see that this means that the star leaves the main sequence and becomes either a red giant or a super giant. This expansion and reddening happens each time the core runs out of fuel and searches for a new source of food. As a result, the stars can move great distances from the main sequence over time. However, as a star lives most of its life on the main sequence, it is the loss of H in the star's core that is the easiest to mark. A star's departure from the main sequence is known as the star's turnoff.

What kind of size difference would we expect to see, though?

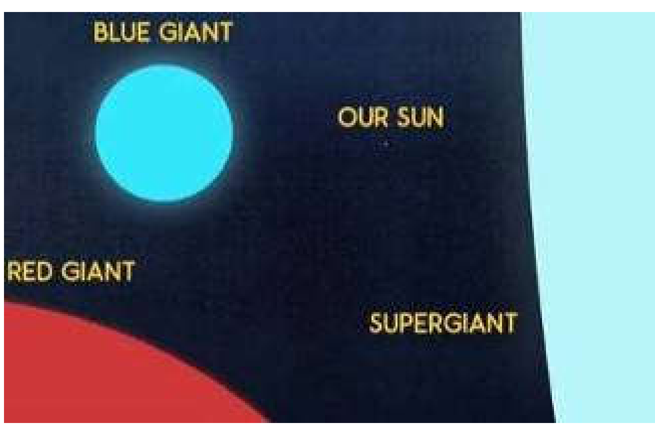
In the case of our Sun, we would expect that the surface of the Sun would reach out and swallow the Earth, possibly even extending out to Mars. We do not need to worry though. We have about 5,000,000,000 years before this is going to happen. Therefore, we have a little more time to crack the problem of space travel, and venture out to explore the Universe before our Sun dies. You never know. We might come back to watch the death of our Sun on the day 5.5/Apple/26 as they did on platform one in the Dr. Who episode 'The End of the World.'

What about stars other than our Sun? How will their mass affect their lifespan? How will their life and their lifespan be affected by the fuel that they burn?

If we start by considering the life of an average Joe, that is to say a low mass star, they can spend 10 - 100,00,000,000 years on the main sequence slowly burning through their H-cores. At the end of this time, they will depart the main sequence, obtaining their middle age spread before puffing up to become red giants.

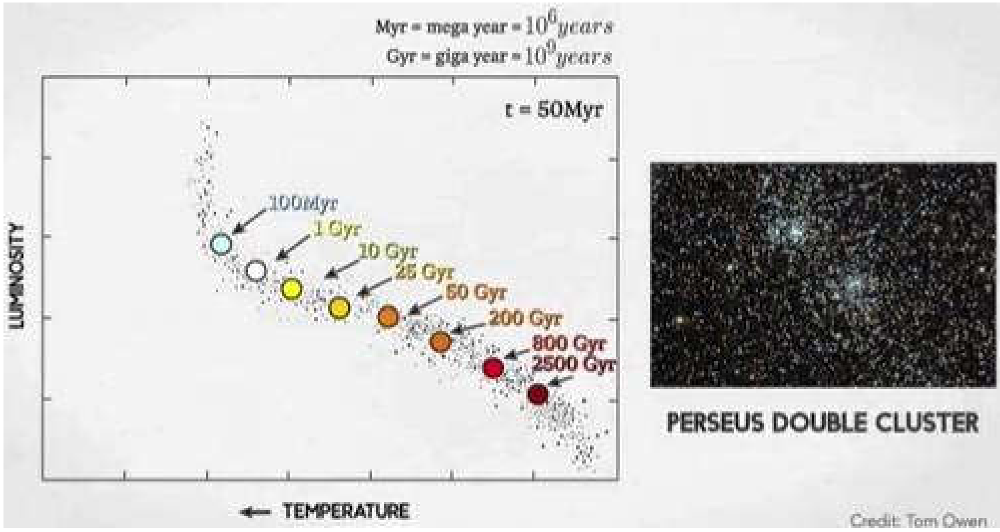
In this phase of a low mass star's life, an average Joe will carry on, plodding along, as it slowly consumes its He-core. At this point, the core will collapse but will never reach a temperature that is hot enough to ignite its C fires. The star will instead end its life quietly, missed only by its family of planets, and its close friends.

What about the rock stars, the high-mass stars? What path do these stars take?

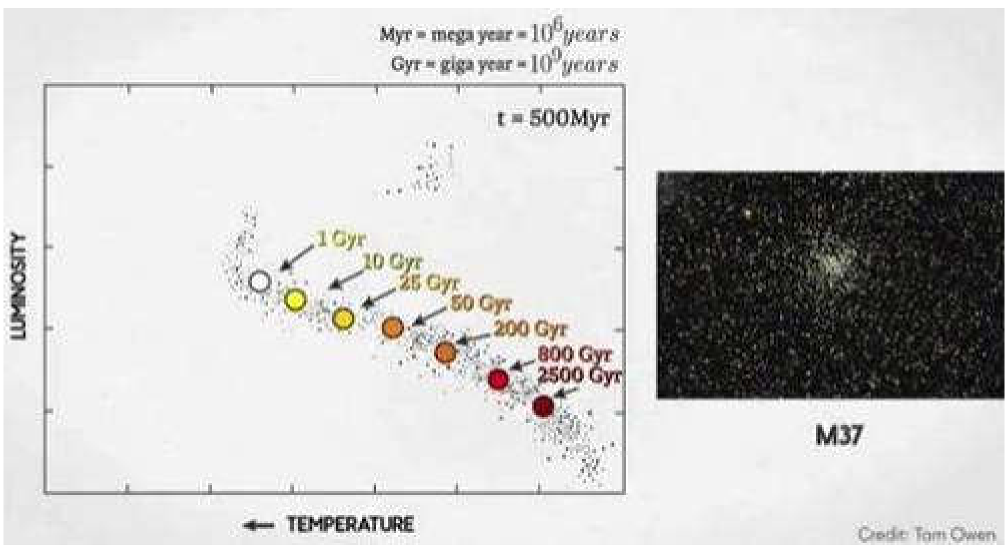


High-mass stars, like many well-known rock stars, live fast and die young, in a huge explosion. Explosions so massive that they can be witnessed in other galaxies. The rock stars in the stellar nursery are more massive, and therefore, contain more H. However, they are also much hotter. High-mass stars burn through their H-cores at a much faster rate departing the main sequence after only maybe 1,000,000 years. At this point, the high-mass star will switch to burning He, then C, a.s.o., building up multiple layers. The number of layers the onion star builds up depends on its initial mass. The more massive the star was at its birth, the closer it can get to a Fe-core. During this time, our rock star will go through a giant, and possibly even a super giant phase as the outer envelope swells, before our rock star eventually dies. The explosive nature of a rock star's ending is explored in more detail later in this module.

Our average Joes and our rock stars were all born in the same stellar nursery. These stars were all born around at the same time, and yet live very different lives at very different paces. By taking measurements of stars to obtain that color and brightness, we are able to learn more about where the star is in its life cycle. However, we can also use this information to find out about the stars that came from the same nursery.



If we take measurements of lots of stars from any given cluster, and when I say cluster, I mean all the nursery graduates that are still around, we can create a HR-diagram for that cluster. This will provide us with a clear view of the current turnoff, the main sequence, within that cluster.



If we check what types of stars are currently turning off, we are able to determine how long they would have been living on their diet of H in their cores. This will tell us the age of the cluster. By taking the measurements of multiple stars, we can tell if this was the graduating class of 100,000,000, 1,000,000,000, or even 10,000,000,000 years ago.

If a cluster is still very blue, then it must be young, while a redder cluster will be old. Clusters of stars change color with age, just as stars do. The hotter bluer stars die out first, then the average stars, and finally the red dwarfs. Eventually all stars die off, resulting in a production of elements that can feed into the next generation of stars. This stellar death is the next avenue to be explored in our journey through the life and death of a star.

8 Life After The Death Of Low Mass Stars

The Sun is a fairly ordinary star. There are stars that are much smaller than the Sun, and also stars that are much larger than the Sun. Stars with larger masses than the Sun are also hotter and brighter than the Sun. Brighter stars produce energy at a faster rate than the Sun, which means that they run out of fuel faster. Bright stars also have a more spectacular death than our Sun. Yes, I said that our own Sun would eventually die. Do not worry though, it would not happen for approximately 5,000,000,000 years, and it will be a rather slow and boring death.

Illustration 60 : Giza pyramids

In case you are still worried about the death of the Sun, let us put 5,000,000,000 years into perspective. We often think about the pyramids of Giza as old, but they were built only about 5,000 years ago, within the realm of written history. Earlier still, the oldest archaeological artifacts from North America's first aboriginal peoples date from 14,000 years ago, which, from an astronomical perspective, is still very recent history compared to the first modern humans, Homo sapiens, which lived about 200,000 years ago.

To put that into perspective, that is about 800 generations of humans or a time when your great, great, great, great, great, great, great, great, great, great, great, great, great, great, great, …, great, grandfather or grandmother lived. In addition, that is only 200,000 years; we will need another 25,000 of those to get to 5,000,000,000.

Illustration 61 : Plesiosaurus skeleton

Let us jump back 1,000 times further. If we multiply 200,000 years by 1,000, we get 200,000,000 years ago, which is the beginning of the Jurassic Age when dinosaurs roamed the Earth and Plesiosaurus, like this one, swam in the oceans. This is also close to the time it takes the Sun to make one full orbit around the center of the Milky Way. That means the Sun celebrates its galactic birthday every 200,000,000 years.

If we multiple 200,000,000 years by 10 we get 2,000,000,000 years, which is when the Earth's atmosphere first became rich in O_2, a milestone in the evolution of plants and animals on Earth. The Sun is still older than 2,000,000,000 years though, since the Sun and the Earth were formed close to 5,000,000,000 years ago. This means that the Sun is not even halfway through its life cycle yet, and it still has about 5,000,000,000 years to go.

8.1 Lifetime Of Our Sun

It is convenient to classify the main sequence stars into two groups. High-mass stars, with mass eight times the Sun's mass or larger, that die in a supernova explosion, and low mass stars with less than eight solar masses that have gentle deaths. When a star runs out of H in its core, it transforms into a red giant star, which is stable for a period of time that is about $^{1}/_{10}$ as long as the time period that it is a main sequence star. For instance, the Sun is estimated to have a total lifetime of 10,000,000,000 years as a main sequence star, and another 1,000,000,000 years as a red giant star. During the red giant, stage of a stars life it swells out to a larger size that could be 10 or 100 times larger than it was during the main sequence. When it swells, its surface cools off, therefore, from Wien's Law its color becomes redder, hence the name red giant.

The star will expand during the red giant phase. During this phase, its mass stays approximately constant, but its radius becomes larger. The acceleration due to gravity depends on a constant divided by the square of the star's radius. This means that as a star expands, the acceleration due to gravity at the surface of the star becomes smaller. If an astronaut visits the star and floats near the surface of the star, the astronaut will feel a weaker gravitational force towards the star when the star expands. This makes it easier for the astronaut to escape from the star's gravitational pull as they leave.

8.2 End Of A Red Giant

What is true for the astronaut is also true for the gas and the outer layers of a red giant star. As the star expands, the star's outer layers are not very strongly attracted to the rest of the star. Any small disturbance can end up pushing the outer layers outwards.

Illustration 62 : Ring Nebula

Eventually low mass stars end up as a red giant that sheds it outer layers into a beautiful cloud of gas confusingly called a planetary nebula. This image is a particular planetary nebula that is commonly called the Ring Nebula. The radius of the nebula is approximately 1 ly across, which is much larger than the size of the red giant whose outer layers disperse to create the nebula. At the center of the nebula, you can see a bright star. That star is a leftover core of what was once a red giant star, and it is called a white dwarf star.

8.3 White Dwarf Star

A white dwarf star is a rather peculiar type of star. The strangest thing about a white dwarf is that it can keep its size constant in time without any nuclear fusion keeping it hot. A typical white dwarf has a mass that is about the same as the Sun, but a size that is closer to the size of the Earth. The composition is mainly C that has solidified into a crystal structure.

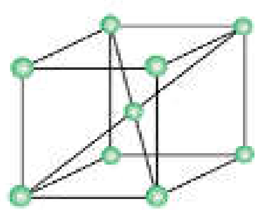


Illustration 63 : Body-centric cubic lattice

8.3.1 Electron Degeneracy Pressure

The electrons zoom around wildly creating an upward pressure that balances gravity. The electrons travel around rapidly due to a quantum mechanical effect called degeneracy pressure. Degeneracy pressure is due to the Pauli Exclusion Principle, which states that particles such as electrons or neutrons are not allowed to exist in exactly the same state. If we were to try to make the particles have exactly the same location with zero speed, they would be identical. In order to keep their identities unique, the particles move quickly with different speeds. As a result, they move around and bounce into each other, creating a gas pressure. This effect does not depend on the temperature. Therefore, if a white dwarf cools down, the degeneracy pressure will keep the star at a constant size. This means that a white dwarf star could potentially life forever.

8.3.2 Planetary Nebula

Illustration 64 : Planetary nebula

When we look at planetary nebula, we always see a white dwarf in the center. UV-photons emitted by the white dwarf ionize the gas in the nebula, causing it to glow with beautiful colors. Over the course of thousands of years, the gas in the nebula slowly starts to disperse and mix with the other gas in between the stars, and the white dwarf cools. After a few tens of thousands of years, the white dwarf will be isolated and will slowly cool down and fade away.

8.3.3 Mass Border For White Dwarfs

Illustration 65 : Subrahmanyan Chandrasekhar

In the early 1900^{s}, astronomers thought that all stars ended up as white dwarfs. That changed in 1930 when a young Indian astrophysicist named Chandrasekhar started thinking about the electrons zooming around in a white dwarf star keeping it from gravitationally collapsing. Chandrasekhar realized that in order to keep a high-mass white dwarf star from collapsing, the electrons would have to travel at faster and faster speeds. If you extrapolate, the prediction is that at some critical stellar-mass, the electrons would have to move at speeds faster than light. Chandrasekhar knew that it is impossible for electrons to travel faster than the speed of light. This led him to calculate the largest mass that a white dwarf star can have. This mass is now called the Chandrasekhar mass, and it is 1.4 times the mass of the Sun.

$$M_{CH} = 1.4 * M_{Sun}$$

Equation 12 : Chandrasekhar mass

8.4 Type IA Supernova

What happens if you try to add extra mass to a stable white dwarf star, that has a mass equal to the Chandrasekhar mass?

Well, electron degeneracy pressure will not be capable of combating gravity, and the star will collapse.

At this point, please watch Astro-101_007.mp4

Video 7 : type IA supernova in a binary system

If the added mass makes the white dwarfs mass go over the Chandrasekhar limit, then the white dwarf will implode. This implosion heats the star, allowing the C in the star to fuse explosively into heavy elements such as U. The explosion destroys the star and sends the heavy elements outwards. This type of explosion is called a 'type IA Supernova.'

8.4.1 Supernova Remnant

After a supernova explosion takes place, there is a hot glowing cloud of gas leftover called a supernova remnant. In the year 1572, the Danish astronomer, Tycho Brahe, observed a bright new star appear in the sky and then fade away. The new star was a supernova explosion.

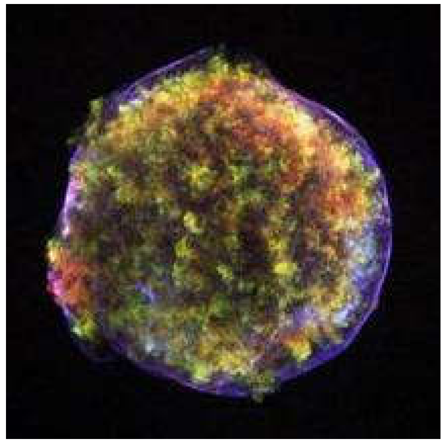


Illustration 66 : Tycho (Supernova remnant)

In modern times when we point a telescope in the part of sky where Tycho Brahe observed the supernova, we see this glowing and expanding supernova remnant. We now call this supernova remnant Tycho, after Tycho Brahe.

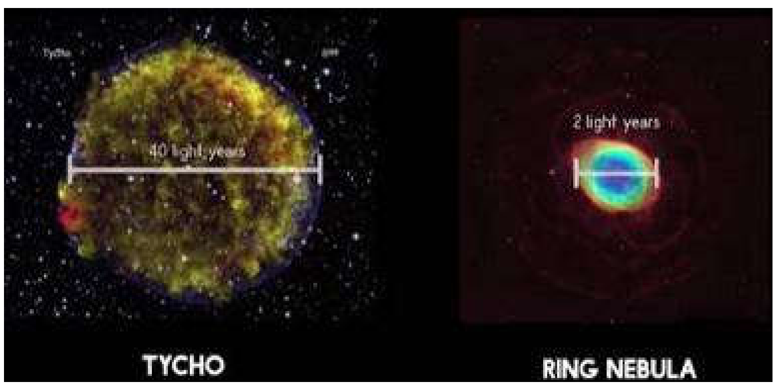


Illustration 67 : Comparison between supernova remnant and planetary nebula

This illustration might look similar to the illustration of the Ring Nebula that we showed earlier, but the Ring Nebula is smooth, while Tycho is very lumpy. This is evidence that the process that formed the Ring Nebula was gentle, while the formation of Tycho was violent. In addition, Tycho is emitting X-rays, while the ring mainly emits visible and UV-light. Point sources of lights are foreground stars that are located between Tycho and us. There does not appear to be any stellar core leftover after the supernova. It is probably true that not all Type 1A supernovas leave behind any remnant star.

Could our Sun die in a supernova explosion?

The Sun will eventually transform into a white dwarf star, but since the Sun does not have a binary companion star, it will not be in any danger of gaining so much weight that it explodes.

9 What Comes Next For High Mass Stars

High-mass stars, larger than eight times the Sun's mass, live through multiple red giant stages, allowing them to transform into giant layered stars with the heaviest elements at the center, and layers of lighter elements lying on top. Eventually, a core of Fe and Ni forms. Since heat-releasing nuclear reactions are not possible in Fe, the star develops an energy crisis. No more nuclear reactions can take place; therefore, the core will cool down, causing the atoms to move slower and the gas pressure to drop. If the core gas pressure drops, it cannot balance gravity, and the star collapses.

At this point, please watch Astro-101_008.mp4

Video 8 : type II supernova (Core-collapsed supernova)

9.1 Neutron Stars

Normally, neutrons do not appear by themselves outside the nucleus of an atom. This is because they are unstable when they are isolated, and decay into a proton and an electron. However, if protons and electrons are forced to come too close together, it is possible for them to combine and transform into a neutron. During the collapse of a core of a high-mass star, the elements are squashed into such a small volume that lots of protons and electrons combine to form neutrons. This leads to a neutron-rich gas that continues to become very dense.

9.1.1 Neutron Degeneracy Pressure

Neutrons are particles that obey the Pauli Exclusion Principle that also governs the electrons in a white dwarf star. The Pauli Exclusion Principle means that the neutrons try to keep their own unique identities, as they are forced to occupy smaller regions of space. The result is that the neutrons zoom around and create a degeneracy pressure that pushes outwards and balances gravity. A neutron star maintains hydrostatic equilibrium through this process that is called neutron degeneracy pressure.

9.2 Jocelyn Bell

Illustration 68 : Jocelyn Bell

The concept of a neutron star was proposed in 1930^{s}, soon after the discovery of the neutron. However, many astronomers doubted the existence of neutron stars and black holes. Most astronomers thought that all stars end up as white dwarf stars when they die.

In 1967, this erroneous belief changed when an astronomy Ph.D. student named Jocelyn Bell observed pulses of radio waves. Jocelyn Bell's goal for her Ph.D. thesis was to observe quasars using a radio telescope. Today, we understand that quasars are super-massive black holes at the centers of galaxies, but in the 1960^{s}, these were mysterious unexplained objects.

9.2.1 Pulsars

During her search for quasars, she found something very different, the pulsed radio emission with very regular pulsation period of 1.337 s. She suspected that this might be a new class of astronomical objects. Therefore, she searched the sky in other directions, and found a few more similar types of pulsing radio sources. These sources of pulsing radio emission were named pulsars. Soon after the discovery of pulsars, it was understood that they are rotating neutron stars. The discovery that neutron stars are possible ends of stellar evolution opened up the possibility that objects that are even more exotic could exist like black holes.

9.2.2 Cas A

Illustration 69 : Supernova remnant CAS A with neutron star

This is the ‘Cassiopeia A’ supernova remnant, which is the gas left over from a type II supernova. The gas has millions of degrees and glows in the X-ray part of the spectrum. The small inset box shows a small point of light, which is the hot newly-formed neutron star found at the center of the supernova remnant. An artist has used his imagination to draw an illustration of what the neutron star might look like, since no telescope has ever imaged a neutron star's surface with more detail than the point of light in this illustration.

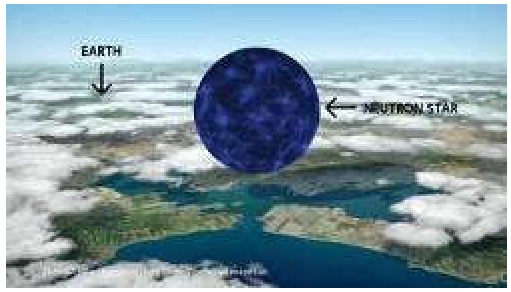


Illustration 70 : Comparison: Earth and neutron star

Neutron stars are tiny stars. A typical neutron star has a radius that is about 10 km, about the size of a city. Remember that white dwarf stars are close to the size of the Earth. Therefore, neutron stars are much tinier.

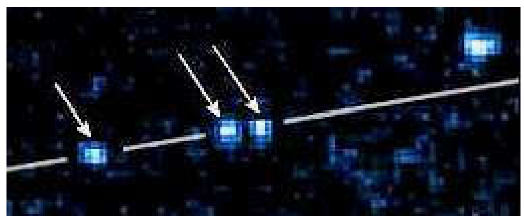


Illustration 71 : Movement of the isolated neutron star RX J185635-3754 (Hubble images)

The only object smaller than a neutron star, but with the same mass, is a black hole. For instance, a black hole with the same mass as a neutron star would be about three times smaller in radius. This is perhaps one of the least visually interesting pictures taken by the ‘Hubble Space Telescope.’ It is an image of the closest neutron star, which is 400 ly away.

9.2.3 Mass Border For Neutron Stars

Most neutron stars are thousands of light years away. It is not possible with today's technology to resolve features on something that small and far away. Just like white dwarf stars, neutron stars also have an upper mass limit. However, unlike white dwarf stars, the value of this upper mass limit is not known exactly. The maximum allowed mass is larger than two times the mass of the Sun and less than three times the mass of the Sun, but we do not really know the value more accurately than this. If a neutron star gains mass above this maximum mass, it will start to collapse probably forming a black hole.

The maximum allowed mass for a neutron star is very important for identifying black holes. Often, we observe X-ray emitting binary star systems. The X-ray emitting properties of neutron stars and black holes are very similar. Therefore, it is easy to confuse one for the other. One way to tell them apart is to measure the mass of the X-ray emitting object, as we will learn how to do later.

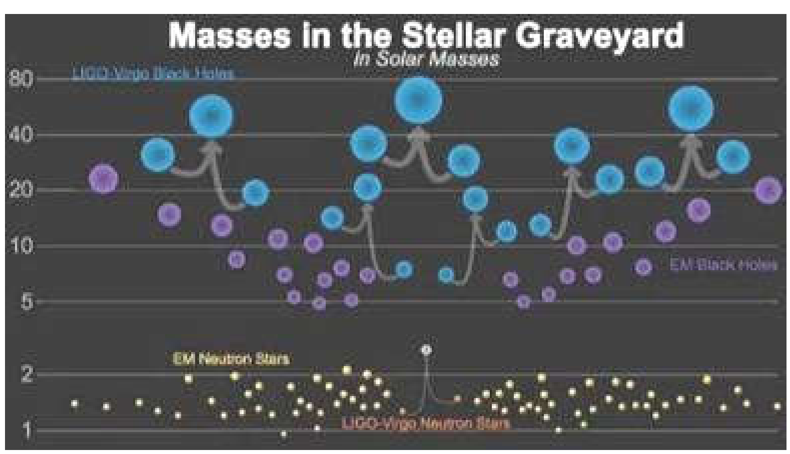


Illustration 72 : Masses in the stellar graveyard

If the mass is larger than three times the Sun's mass, then it is a black hole. If the mass is less than three solar masses, then it could be either a neutron star or a black hole. In all cases where the mass is smaller than three solar masses, astronomers have found some other evidence such as post emission from the surface, which allows for identification as a neutron star.

9.3 Formation Of Black Holes

The highest mass main sequence stars are thought to form black holes when they run out of fuel. There are still many open questions about how black holes form.

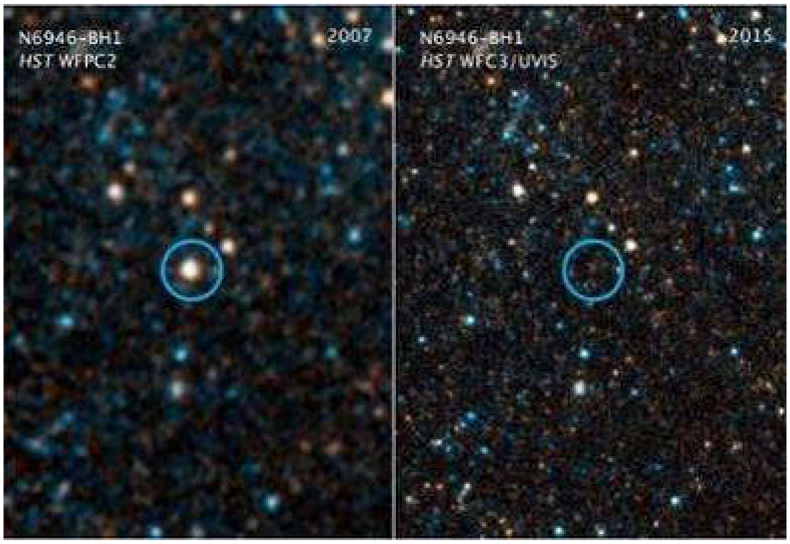
How massive must a star be to form a black hole?

The standard limit that is usually quoted is that the mass when it was main sequence star should be larger than 30 solar masses. However, this limit is not really known that accurately. It could be a bit smaller or a bit larger.

One way to produce a black hole suggested in the 2009 'Star Trek' movie is to inject a planet with something called red matter. We have no idea what red matter might be; therefore, this is definitely in the realm of science fiction.

Some core-collapse supernovae might produce black holes instead of neutron stars. Astronomers carefully examine supernova remnants to see if any evidence of a black hole instead of a neutron star can be found. So far, there has not been any discovery of a black hole found inside of a supernova remnant. However, since black holes are difficult to detect, this does not necessarily mean that there are not any.

9.3.1 Failed Supernova



Another idea is something called a failed supernova. The left image from 2007 shows the red super giant star N6946-BH1, which has a mass that is about 25 times larger than the Sun. In 2015, an image of the same star field shows no star. Astronomers did see the star get a little bit brighter, but there was no supernova explosion before it disappeared. Astronomers are now carefully watching this region to look for signs of the formation of an accretion disk. It is possible that we actually have caught a star in the act of collapsing to form a black hole.

9.4 Hypernova (Collapsar)

Alternatively, in some cases it might be possible for the birth of black holes to produce a burst of γ-rays. γ-ray bursts are short-lived bright burst of γ-rays generally seen in faraway galaxies.

At this point, please watch Astro-101_009.mp4

Video 9 : Hypernova, viewed by γ-ray telescopes

10 Summary: The Circle Of Live

All stars are born from the creation of interstellar gas and dust. When enough H- and He-gas secretes by the forces of gravity, stable nuclear fusion sets in at the core of the new star. Small stars burn for many billions of years and enjoy a long retirement before their gentle end. We are lucky that our own Sun is one such middle-aged star. Humanity and all life on Earth will continue to enjoy the Sun for billions of years to come.

On the other hand, large stars ones with more than eight times our Sun's mass live life on the edge. They burn through vast amounts of H and He, and continue to brighten as they fuse heavier and heavier elements. Just like a rock star who lives life on the edge, the fast pace is enough to wear out anyone. Massive stars rock and roll into early deaths and violent ones at those supernova explosions.

Not all stars that explode at the end of their lives end up as black holes. Only stars, which are much more massive than our Sun, go on to produce black holes. Hydrostatic equilibrium is the principle that explains why stars do not collapse at different stages of their life. Each of the remnants, white dwarf stars, and neutron stars depend on different types of pressure to maintain their surfaces.

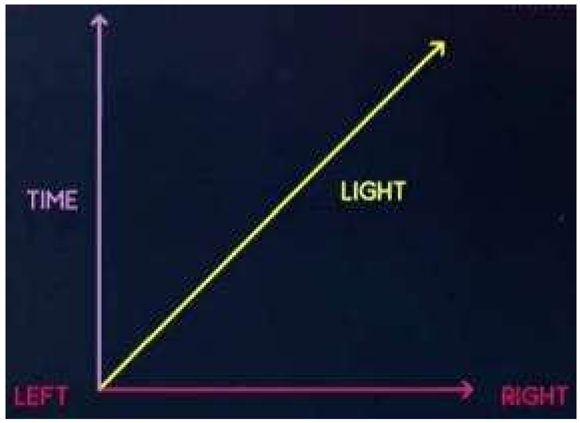
However, black holes do not have a surface per se, because there is no force strong enough to overcome the force of gravity around the black hole. Black holes generate such a strong gravitational field that they permanently warp space and time creating a hole in the fabric of the Universe.

The Structure Of Space Time

1 Introduction

In order to understand more about black holes, we need to understand the concept of space-time. Most people are familiar with the concepts of space and time, and think of them as separate quantities. However, Einstein's theories of 'Special and General Relativity'[2] show us that different observers do not agree on measurements of distance and intervals of time. What everyone can agree on is the mixture of these two concepts in the framework called space-time.

1.1 Spacetime



Spacetime is used to explain all of the strange effects we encounter in the theories of special and general relativity.

Why is the speed of light the ultimate limit in the Universe? Why do moving clocks run slowly compared to stationary clocks?

An interesting way of understanding the basic properties of black holes is to consider a simple example involving sound waves instead of light. In 1972, black hole physicist William Andrew devised a thought experiment consisting of a fish calling out to its friend as a falls over waterfall. At a certain point in the waterfall, the speed of the water exceeds the speed of sound and the falling fish can no longer be heard by its friend above.

This is an example of a sonic black hole, an analogy that uses sound waves instead of light waves to help us understand black hole physics. Of course, this example makes many assumptions. For one, I do not know how a fish would yell underwater, but that is beside the point. Let us dive right in, and see how a fish experiences water as space-time, and what it can tell us about the nature of black holes.

2 Fishing in Space Time

At this point, please watch Astro-101_010.mp4

Video 10 : William Andrew's thought experiment

3 Introduction To Special Relativity Theory

Just as sound waves propagate in water, it was once believed that light waves propagate in a medium called 'Aether.' This presented an opportunity for experimental physicists to measure the motion of the Earth with respect to the 'Aether.'

3.1 Michelson-Morley Experiment

In 1887, two scientists named Michelson and Morley conducted an experiment to do just that. However, no matter which the direction they pointed their apparatus, they measured the same speed of light through the Aether. This forced them to conclude that the Aether did not exist, and that light would always be seen traveling at the same speed.

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[2] For further information watch this: [Albert Einstein and his Greatest Work: General Relativity E=mc²]

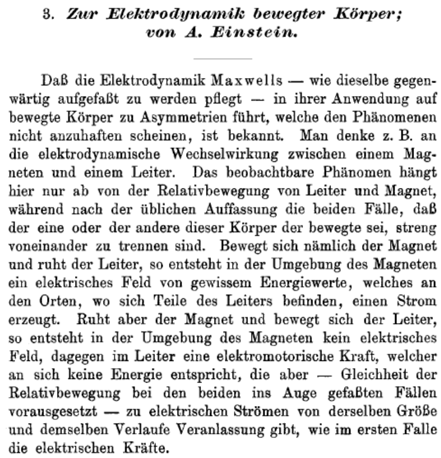
3.2 Einstein's Postulates

This puzzled scientist's worldwide, well, except for one, Einstein. Einstein imagined what it would be like to see the Universe from the perspective from a beam of light. He asked questions like:

How would a photon perceive the passage of time? Will distances shrink and stretch depending on the motion of an observer?

Of relevance to him was the fact that experiments had proven that light waves were special compared to sound waves or water waves. In that, they did not require a medium through which to propagate.

In helping us to understand these new revelations, Einstein had to tackle problems, which few could ever even consider.



3. ***Zur Elektrodynamik bewegter Körper;***
von A. Einstein.

Daß die Elektrodynamik Maxwells — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Magneten und einem Leiter. Das beobachtbare Phänomen hängt hier nur ab von der Relativbewegung von Leiter und Magnet, während nach der üblichen Auffassung die beiden Fälle, daß der eine oder der andere dieser Körper der bewegte sei, streng voneinander zu trennen sind. Bewegt sich nämlich der Magnet und ruht der Leiter, so entsteht in der Umgebung des Magneten ein elektrisches Feld von gewissem Energiewerte, welches an den Orten, wo sich Teile des Leiters befinden, einen Strom erzeugt. Ruht aber der Magnet und bewegt sich der Leiter, so entsteht in der Umgebung des Magneten kein elektrisches Feld, dagegen im Leiter eine elektromotorische Kraft, welcher an sich keine Energie entspricht, die aber — Gleichheit der Relativbewegung bei den beiden ins Auge gefaßten Fällen vorausgesetzt — zu elektrischen Strömen von derselben Größe und demselben Verlaufe Veranlassung gibt, wie im ersten Falle die elektrischen Kräfte.

Illustration 73 : On the electrodynamics of moving bodies by Albert Einstein (Original text)

In one of Einstein's most famous papers entitled 'On the Electrodynamics of Moving Bodies,' he introduced two very important ideas. Ideas, which are now among the foundation of modern physics. They are:

1. The laws of physics are the same in all inertial frames of reference
2. Light moves at the same speed relative to all observers

That first postulate seems reasonable. The laws of physics are the same for me here as they are for you sitting there. The laws of physics are the same on the Moon as they are here on Earth. In physics, this principle is essential, as we use it all the time in order to learn about places that are distant from us.

An inertial reference frame is either an experiment at rest, or one moving with a constant velocity. Inertial frames are not accelerating. For example, someone standing in a high-speed train would experience the same laws of physics as someone stationary on the ground, so long as neither is accelerating. The first postulate is intuitive to human beings, which makes the second one impossibly hard to believe at first glance.

Einstein's second postulate was that light moves at the same speed relative to all observers. Therefore, if we were to measure the speed of light from a fast moving astronaut, we do not add the astronaut's speed to the speed of light.

Weird, right?

The speed of light always comes out to the same value, no matter how fast the astronaut is traveling. Einstein realized that if the laws of physics are the same for all observers, then all observers must agree on the value of the speed of light.

You have probably experienced some of the strange effects of changing reference frames before.

Have you ever been in a parked car when an adjacent car starts moving?

In some cases, your brain tricks you into thinking that you are moving instead of the other car. Since motion is relative, we can always choose a reference frame that is stationary, even if there is relative motion to something else.

Let me explain!

At this point, please watch Astro-101_011.mp4

Video 11 : Experiment by thought about speed of light

Einstein thought so, too. Clearly, if Einstein's second postulate, that all observers measure the speed of light as a constant, is to hold true. We need some other kind of transformation group, therefore, that every observer can see the light beams moving relative to themselves, at c. In order to do such a thing, Einstein realized that our intuitions about space and time must be incorrect. Moreover, that a new theory is required to describe how all observers, moving at different speeds, can measure the speed of light to be a constant.

4 Spacetime

Last section ended with the idea that the speed of light is the same in all inertial frames. Now let us connect this to the idea of space-time and events.

Two astronauts moving at constant speeds relative to one another will measure the speed of light from all sources of light to have the exact same value, which we write as c.

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

A constant speed is just the distance traveled by the time that has elapsed. Einstein realized that one way to explain why two astronauts moving relative to each other measure the same speed of light is, because the two astronauts do not agree on the definitions of space and time. Instead of thinking about space and time as separate concepts, Einstein realized that he needed to consider the combination of both space and time into a concept he called space-time.

The Universe consists of four dimensions. Three of those dimensions are spatial moving in the up-down dimension, the left-right dimension, and the forward-back dimension. The last dimension is time, the past-future dimension. Although, we do not say something moves in time, just that the flow of time itself moves us towards the future and away from the past at a speed of 1 $^{s}/_{s}$.

Let us exercise our imagination to understand better, how humans perceive time. Our senses collect information from the space around us, but we exist only at a single moment in time. None of our senses can perceive the passage of time directly or changes in time for that matter. The best humans can do is to create memories of the past, which allows us to affect change in their future environment. In that sense, we only experience a narrow slice of time.

How do we effectively imagine what a four-dimensional space-time looks like?

Well, let us start by considering an easier illustration with fewer dimensions altogether. Suppose my fingers are limited to motion in only one spatial dimension like walking along my arm. I can move those forwards along my arm or backwards along my arm. However, it is too narrow for left and right, and my fingers are too weak for up and down. In essence, I have compressed three dimensions of space into a single dimension. My fingers position can be characterized by a single point along a line.

4.1 Spacetime Diagram

If the fingers walk along my arm from elbow to hand, it takes some amount of time. Since we have my fingers distance on the horizontal axis, let us now plot time along the vertical axis. This diagram is called the space-time diagram. Since we humans only see a narrow slice of the spatial dimensions, we need to reveal how my fingers position changes with time.

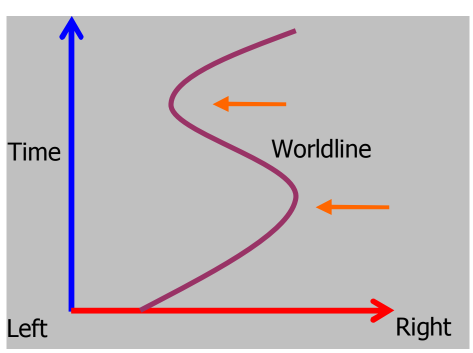


Illustration 74 : Spacetime diagram of moving fingers I

This curve, for example, shows that my fingers walk back and forth across my arm, and also move forward in the time dimension. If we mask everything but a narrow slice, we get back to the original representation of my fingers position in space. This path is my fingers worldline.

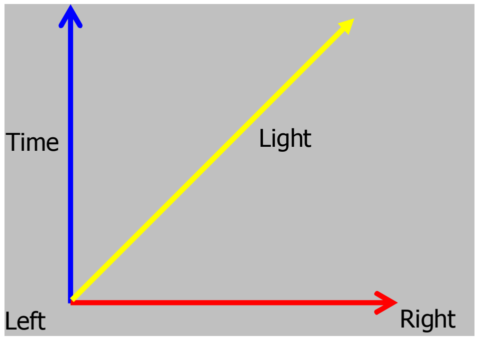


Illustration 75 : Spacetime diagram of moving fingers II

Since photons must travel at the speed of light, a plot of position of a photon on a space-time diagram will zoom outwards in a perfectly straight line. Normally, this line is drawn therefore that the light ray makes a 45° angle from the space and time axes. Anything that travels at speeds less than light, such as people and rockets, have worldlines that stay in the region between the time axis and the worldline of the light ray. The only way to escape from this region is to move faster than the speed of light.

This diagram only shows light moving to the right. However, light can also move to the left. Moreover, the left moving light will also be represented by a line that makes a 45° angle to the space and time axis.

4.1.1 Light Cone

This diagram shows only one dimension, the left-right dimension. However, also a back-forth dimension comes in and out of the screen that we are not showing. Light also travels at 45° angles to the back-forth dimensions axis. The 2D-surface that light can travel on is called the light cone. In addition, there is a third dimension, up-down, and it would be difficult to show this dimension in a drawing of this sort.

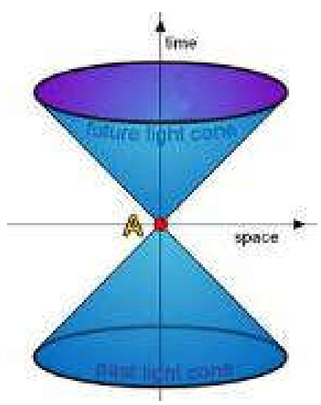


Illustration 76 : Light cone

In a space-time diagram, the light cone defines the boundary of space-time events that a person or any object that travels at speeds slower than light can experience. People can travel upwards in the time dimension in directions that stay inside the light cone. Experiencing events outside of the light cone would require that we can travel faster than light. This means that people and all objects with mass are confined to our own personal light cones.

It is hard to convey what space-time actually is. One way to visualize space-time is to imagine a 3D-object, and then try to extend its dimensionality across time. A person is human-shaped in 3D, but in 4D-space-time, a person is a long tube that includes the person in the past, present, and future. If you slice this 4D-tube in the time dimension, a 3D-version of the person at that moment in time is the slice.

The 4D-space-time we live in is similar to a block of cheese if we reduce space-time to only two dimensions. We can imagine the ends of this cheese as the two space dimensions, and the length of the cheese as the time dimension. Therefore, a hole in cheese becomes a cheese being, living inside of a block of cheese-time or space-cheese or space-cheese-time. You get the idea.

A cheese being at rest thinks of time running along the long axis of the cheese, and the 2D-space that it lives in is the flat end of the cheese. Humans are all powerful higher dimensional beings with a cheese knife, and we can slice up the block of cheese into thin slices. Each slice of cheese represents a single moment of time as experienced by the cheese being.

At one end of the cheese, there are no cheese beings, but as we slice through their time dimension, we discover the birth of a cheese being, growing to larger sizes, and eventually disappearing. Just like our 4D human tube from our perspective, a cheese being has been born, lived a fruitful life, and died a cheesy death.

Here is where things get interesting though. A different cheese being that moves at a constant speed through the cheese will slice up the cheese in different direction. The moving cheese being will see different size slices, and think the times and sizes are different as if the cheese space-time itself were somehow worked. However, if we were to take the same cheese block and slice it up in yet another direction, we can do it such that both observers agree on where the bubbles are in space-time, but they cannot agree on how it was sliced. We can only speculate whether Einstein used cheese to describe space-time. However, if he did, surely we can all agree that it must have been tasty.

5 Effects Of Special Relativity[3]

If you decide to hold a party, you need to tell your guests where and when they should arrive. It is not enough simply to tell your friends where the party is without telling them when it occurs, or vice versa. Therefore, when we use the word event, we are using it to describe where and when something is happening.

5.1 Event

Events can describe things like your arrival at a party, the time you spilled your drink, or even something as simple, as snapping your fingers can be an event. I could say that I snapped my fingers about 5 s ago at this location right here. Therefore, an event must include details of both the position and the time.

5.2 Dimensions

Our Universe has three spatial dimensions. Therefore, a defined event could look something like x, y, z, and t. where x, y, and z define the position, and t defines the time. A good example of this occurs in popular TV-show 'Big Bang Theory.' In an episode entitled 'The Cushion Saturation,' Dr. Sheldon Cooper explains the first time, he sat on his favorite spot on the couch as follows:

'In an ever changing world, it is a single point of consistency. If my life were expressed as a function on a 4D Cartesian coordinate system, that spot, at that moment I first sat on it would be 0,0,0,0.'

[3] For further information use this link: special relativity

Sheldon feels most comfortable and at home at the *x*, *y*, *z* coordinates of his spot, or 0, 0, 0. Although he can return to the spot on the couch many times, and he does, he can never return to the exact moment when he first sat on the couch to experience that event again. The reason for this is that the fourth coordinate in the event is time, *t*, and is it always increasing as time passes.

Suppose he originally sat down to enjoy a 40-minute episode of 'Star Trek.' We can describe the end of the show as an event that happened at 0, 0, 0, 40 minutes. The only way to return to the original event would be to use a time machine, such as the one Leonard Hoffsteader took a ride in 'Big Bang Theory' episode 'The Nevada Annihilation.' If we were to return to Sheldon's first time on the couch, and saw Penny riding a skateboard past the scene, Sheldon would see her in his reference room.

Would Penny see the first moment he sits in that spot followed by a 40-minute episode of 'Star Trek' in the same order Sheldon experiences it? Considering our previous discussion about slicing of space-time, do you think all observers see the two events in the same order, or with the same time interval between the events?

Let us explore this further using one of Sheldon's favor objects, trains.

5.3 Relativity Of Simultaneity

Sheldon is preparing for a trip on the 'Napa Valley Wine Train' in his favorite 1915 Pullman-standard lounge car.

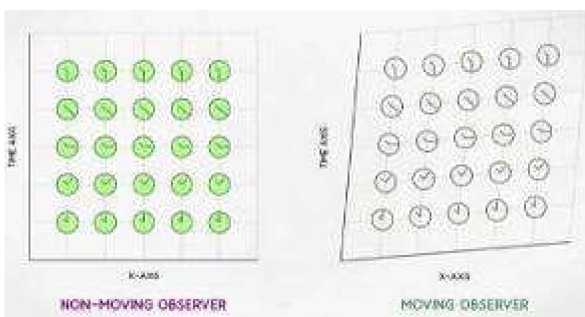
At this point, please watch Astro-101_012.mp4

Video 12 : Relativity of simultaneity

As strange as it seems, both Sheldon and his friends on the train are right. In some cases, the order of events depends on the motion of the observer. Einstein explained this through the concepts of length contraction and time dilation.

Why observers in different reference frames do no agree about events?

Well, think back to our block of cheese space-time analogy. A moving observer, relative to another observer, actually slices up space-time differently. Not only can they potentially see events in different order than other observers, but they also measure length and time differently.



Have a look at this graph, which represents space-time for a stationary observer. A stationary observer sees objects as they naturally are, and clocks run as expected. However, a moving observer sees space-time through a different slice. Here is what space-time looks like to a moving observer. Both the moving observer's time axis and distance axis have shifted. Physicists say that the time and space-coordinates are rotated due to the motion of the observer. This is a convenient illustration to paint.

What are the real observable effects of this skewed reference frame?

5.4 Length Contraction

Earlier we mentioned that moving observers measure changes in length and time. Length contraction is given by the equation:

$$L = L_0\sqrt{1-\left(\frac{v}{c}\right)^2}$$

Equation 13 : Length contraction

What this equation describes is how the length of the object appears to a moving observer. If I jump into a spacecraft, and I am moving at nearly the speed of light, objects I observe will appear to shrink in my direction of motion. Something like the planet Earth would pass by the ship appearing to be almost as flat as a pancake.

5.5 Time Dilation

It is not just length that changes, though, time also changes. Time dilation is given by the equation:

$$t = \frac{t_0}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

Equation 14 : Time dilation

In this case, time is modified by dividing by these terms under the square root sign. Instead of decreasing, the time observed by the moving observer increases. Therefore, the moving observers see all external clocks slowing down the faster they move. Both length contraction and time dilation are effects that are measured by a moving observer. The faster the observer moves with respect to any object such as a clock, the thinner it appears and the slower it takes.

I hope that your head is not spinning too much yet, because we have to discuss an important issue with special relativity.

Since a moving observer appears to be stationary in their own frame of reference, whom can we trust when they say that the lengths have been contracted and the clocks have been slowed?

To illustrate this problem, we need to introduce you to the twin paradox.

5.6 Twin Paradox

Let us imagine that twins named Leah and Luke are preparing for an interstellar voyage. Leah will stay behind on Earth to monitor the journey, while Luke, the adventurous one, takes off in his spaceship capable of reaching nearly the speed of light. Since Leah stays on the Earth as Luke speeds away, Luke's clock appears to slow down the faster he zooms off in his ship. However, to Luke, Leah appears to be speeding away. Therefore, to Luke, Leah's clocks have slowed down. Both observers see the other clock as being slow, while their own clocks are at regular speed.

How can that be?

Surely, both observers cannot be right. Welcome to the twin paradox proposed by Einstein, not as a paradox, but as a peculiarity of special relativity. In Einstein's 1905 paper, he reasoned that if two clocks were synchronized, and one of them was to go on a lengthy journey, the traveling clock would return to the original location with its time lagging behind the stationary clock.

Since Relativity says that either clocks could view the other as being the one in motion, that is the traveling clock could consider itself at rest, and the stationary clock would therefore be the one moving away, should not the stationary clock be the one lagging behind when the other returns again?

Most explanation of the twin paradox talks about the acceleration of the traveling twin. It is the traveling twin that experiences the effects of time dilation, returning to Earth much younger than returning to the twin who stayed behind. However, the twin paradox can be explained without accelerations at all.

Let us watch as Luke flies to a nearby star system six light-years away while Leah stays behind on the Earth. Luke can travel at a significant fraction of the speed of light, say 0.6 c. When we say that something is traveling at 1 c, it is the same as saying that it goes 1 $^{ly}/_{year}$. Therefore, if Luke travels at 0.6 c, he will travel 0.6 of 1 ly for each year of travel. As such, Leah will say that Luke's journey takes 10 years.

However, let us carefully assess what Luke observes on his particular journey. Luke sets his spaceship to travel at 0.6 c. In doing so, the distance to his destination changes. At 0.6 c, the length between the Earth and the destination has shortened by 25 %. Therefore, instead of 6 ly, the star appears to be only 4.8 ly away from Luke's perspective.

At 0.6 c, Luke's time of arrival is only 8 years after his departure from the Earth. To Leah, this is compounded by the fact that she cannot receive any signal from Luke marking his arrival in the nearby star system, as any signal Luke sends will come back to Leah on the Earth will travel at the speed of light. This means that Leah does not even get Luke's arrival note until 16 years after departure.

Meanwhile, Luke has turned his ship around and begins his journey back to Earth; again, at 0.6 c. Therefore, the same length contraction applies. Instead of flying across 6 ly of space, Luke only flies the length contracted to 4. ly. Moreover, he is back from his distant star system after another 8-year journey. For Leah, Luke has been gone for 20 years, but from Luke's perspective, he has only been gone 16 years. Luke is now 4 years younger than Leah is.

I hope that you can now see why Einstein said this was a peculiarity, and not a paradox. Luke as the moving observer sees space itself foreshortened, but in Leah's reference frame, the distances have not changed, merely the shape of Luke's ship. We have seen the square root equation come up twice already.

What is it?

5.7 Lorentz Factor (γ-Factor)

$$\sqrt{1-\left(\frac{\nu}{c}\right)^2}$$

Well, this is a useful little equation that represents the strength of the time dilation or length contraction based on the speed of the moving observer. It is more commonly found in this form:

$$\gamma(\nu)=\frac{1}{\sqrt{1-\left(\frac{\nu}{c}\right)^2}}$$

Equation 15 : Lorentz factor

Called the Lorentz factor, or the γ-factor. The Lorentz factor is a convenient tool when discussing length contraction and time dilation, because it converts these equations

$$L=L_0\sqrt{1-\left(\frac{\nu}{c}\right)^2} \qquad t=\frac{t_0}{\sqrt{1-\left(\frac{\nu}{c}\right)^2}}$$

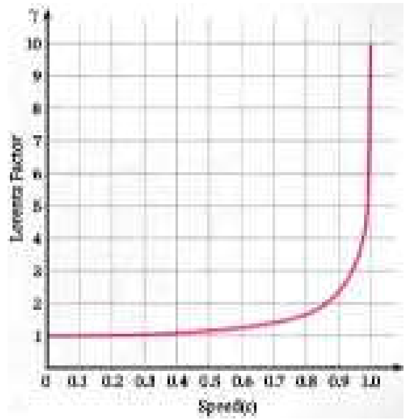
into these vastly simpler forms.

$$L=\frac{L_0}{\gamma(\nu)} \qquad t=\gamma(\nu)t_0$$

Speed (ν/c)	Lorentz factor
0	1
0.1	1.005
0.2	1.021
0.3	1.048
0.5	1.155
0.8	1.667
0.9	2.294
0.99995	100
1	∞

Table 1 : Speed / Lorentz factor conversion

Therefore, someone traveling at 10 % of the speed of light, or 0.1 c, sees a 0.5 % shortening in the length of a stationary object, and a 0.5 % increase in the flow of time. That is not that much. Moreover, even at half the speed of light, it is only a 15 % change. You need to be traveling at almost the speed of light to see significant changes. At 90 % of the speed of light, the Lorentz factor is < 2.



Here is a graph illustrating how quickly the Lorentz factor changes at very high speeds. We should note that Einstein develops special relativity to describe physics for observers who are not experiencing a strong gravitational force.

What happens near an object with strong gravitational field, such as a black hole?

Einstein realized that he had to modify his theory of special relativity to make it more general and to allow for gravity. Einstein called this relativistic theory of gravity general relativity. In order to understand the theory of General Relativity, we will begin with Einstein's first ponderings on the subject, something called the equivalence principle.

6 The Equivalence Principle

If humans decide to explore other solar systems, we will need to get there using generation ships. Ships like these can carry a self-sustaining human colony, which can survive for many generations. This is the premise of a television series called Ascension. The characters in the show walk around as if they are in Earth gravity, which is generated by the acceleration of their ship.

Without windows to see outside, can the characters tell the difference between uniform acceleration of their spaceship or simply being stationary on Earth's surface?

Suppose you awaken in just such a situation, you are trap in a small room unable to remember how you got there and with no way of seeing what is outside.

Could you tell the difference between the room being here on Earth or in an accelerating rocket ship?

Einstein realized that these to scenarios are indistinguishable as long as the room is small enough.

In an experiment, that you could try in your small room is to drop a ball. There are two possible outcomes depending on where the room is. If it is here on Earth, the ball will appear to accelerate downwards, falling to the ground due to gravity. In the second scenario, we are in an accelerating rocket ship far away from any sources of gravity, the ball still appears to fall, only this time, and it is because the rocket is accelerating upward. If the acceleration of the rocket is precisely $9.81\, {}^{m}/_{s^2}$, the motion of the ball will be indistinguishable from the effects of gravity on Earth. Nice try, but dropping the ball will not tell you which of the two scenarios you are in. You might say that you dropped the ball by dropping the ball.

Not knowing whether it is the rocket ship accelerating or the ball accelerating due to gravity is called the equivalence principle. In fact, the formal definition of equivalence principle given by Einstein himself states, 'We assume the complete physical equivalence of a gravitational field and a corresponding acceleration of the reference system.' What Einstein discovered is that gravity is not a force, as it was believed to be by Newton and classical physicists. In small regions of space, gravity is indistinguishable from acceleration.

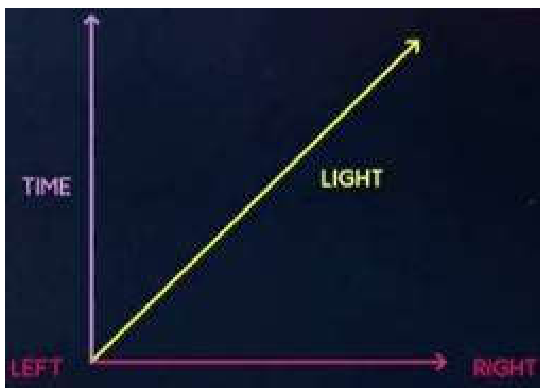
Now we should note that Einstein's statement of the equivalence principle requires that your choice of a reference frame is small. Earth's gravity for example does not change much between your toes and your head. However, if you chose a tall reference frame, or an extremely wide reference frame, it would become pretty obvious that you were on Earth. Just by measuring changes in gravity as you moved around. Gravity would become weaker the higher you were from Earth's surface. The force of the gravity on the surface always points to the center of the Earth. Therefore, if you have a large horizontal frame, the direction of the balls will fall becomes different.

The converse of our ball analogy is also true. When an astronaut is orbiting the Earth, they appear weightless because they are in free fall. In free fall, the force due to gravity is exactly matched by the centripetal acceleration towards the Earth. This is similar to riding your favorite drop of doom style amusement park ride where you feel temporarily weightless.

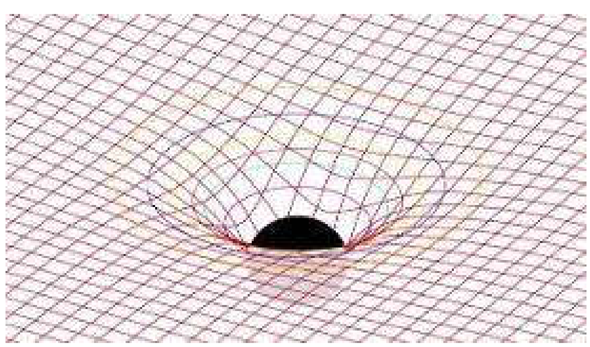
Astronauts are in a perpetual drop of doom. This would be indistinguishable from an astronaut who has run out of fuel far from any sources of gravity. Many science fiction shows, including ‘Star Trek,’ portray artificial gravity, but failed to explain the technology necessary in order to produce these fields. However, some science fiction gets it right. In the movie ‘2001, A Space Odyssey’ and ‘Interstellar,’ gravity is produced by rotating the spacecraft to introduce centrifugal acceleration, which mimics gravity. An example of the equivalence principle at work.

If a ball thrown on Earth travels on a curved path due to gravity, we would expect the same curvature to occur on an accelerating rocket ship. Einstein's explanation of gravity introduces the idea of the thrown ball's trajectory being the shortest possible path through a curved space-time. Gravity itself, Einstein believed, was the result of space-time being curved by mass and energy.

7 Curved Spacetime



One of the most important realizations Einstein made while developing special relativity is that there is no such thing as a universal time or distance. Instead, special relativity introduced the notion of an invariant space-time interval. When astronauts travel at different speeds and experience differences in the duration of time intervals, they are effectively trading distance for time or vice versa. They are experiencing a distortion or warping of space and time together. This is required in order for all observers to agree on the speed of light. Einstein realized that he could explain the effects of gravity by combining the equivalence principle with the concept of an invariant space-time interval used in special relativity.



When Einstein developed the general theory of relativity, he came to the realization that gravity is the warping of space-time. Stars like our Sun, which have strong gravitational field due to their large mass, actually bend and stretch the fabric of the Universe itself. The warping of space-time causes planets and light to travel on curved paths near massive objects.

Illustration 77 : Total eclipse of the Sun

An early test of general relativity depended on the bent space-time around the Sun. In 1919, the astronomer, Sir Arthur Eddington, led an expedition to an island of the West Coast of Africa in order to measure how much the gravity of the Sun warped space-time. They did it by observing a total eclipse of the Sun. During the eclipse, a star could be seen next to the eclipsed Sun. Those of you, who have observed a total solar eclipse, as I have, know that the Sun looks eerily like a black hole in the sky surrounded by white hair.

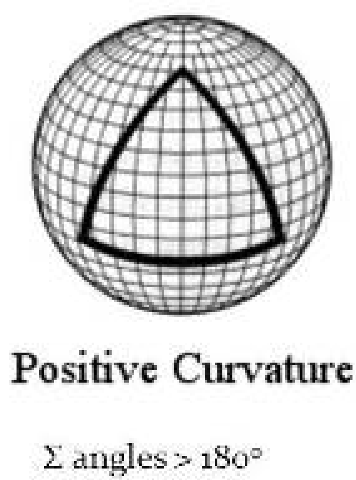
The locations of all the stars in our neighborhood of the galaxy were mapped more than 100 years ago. Therefore, it was known that this star should really be located behind the Sun when viewed from the Earth on the day of the eclipse.

How did Eddington and his team see the star?

The light from the star traveled on a curved path around the Sun to the astronomers' telescopes. This effect was predicted by Einstein's theory of general relativity. The measurement they made confirmed and has since been reconfirmed that the theory of general relativity is accurate and that space-time itself has been by matter.

These changes are notion of what a straight line is, of course, because if space-time itself is bent, how can we possibly know that we are going in a straight line?

Instead of calling them straight lines, in general relativity, we call them geodesics, which represent the straightest possible path of an object in a curved space-time. Even though geodesics represent straight lines in curved space-times, they would not be considered straight by our standards. Just as the Sun's mass bends the space-time around it, any light crossing bent space-time will appear to have its path bent.



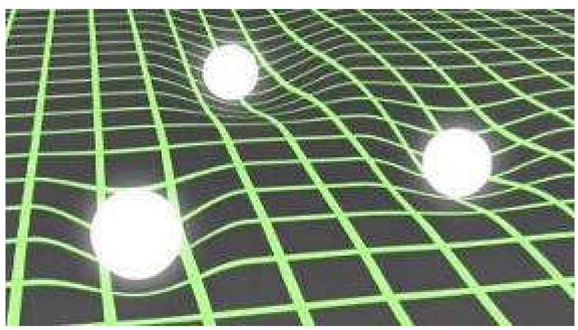
Since we are talking about curving space-time, let us consider the surface of a ball as a section of a curved 2D-space. This works equally well if you imagine the ball to be the Earth. If I asked you to draw a straight line between two points on opposite sides of the ball, the same thing as asking for the flight path between two cities on Earth, you might be tempted to draw along an equatorial line to join them together. Even though I asked you to draw a straight line, already it is curved. Instead, the smallest distance between two points on a curved surface is considered straight if it is also the shortest line joining the two points together.

7.1 Geodesic

The smallest distance between two points on a curved surface is called a geodesic. If you look at the flight path of an airplane from Toronto to London, the airplane crosses the ocean near Greenland. The shortest route joining the two cities is a curved path. The same is true for any object traveling through curved space-time.

Where do you think the most convoluted curvatures of space-time in the Universe exist?

That is right, black holes. Not only do black holes warp space-time, they warp it to the point that even light will travel on highly curved paths. Photons, by definition, travel on geodesic paths in space-time. Close to the black hole, the curvature becomes so high that light is bent into paths that all terminate at the black hole's singularity.



General relativity interprets gravity as the warping of space-time. When we view an illustration of the gravitational field around a massive object, it is usually represented as a depression in space. However, we need to understand that gravity also warps the passage of time. It is strangely difficult for the human mind to grasp the concept of warping space-time. We understand what it means to bend or warp a material like plastic.

What does it mean when the actual space and time that we live in are bent and twisted?

7.2 Gravitational Time Dilation

In a sense, warped space-time means that the paths we choose to cross space and time will be shorter or longer in distance between two points and in the duration, it takes to travel between them depending on what the gravitational fields are along the path. Let us focus specifically on how gravitational fields warp the time component in an effect called gravitational time dilation.

Let us start with an example by considering two astronauts exploring an unstudied planet around a distant star, perhaps planet e in the nearby Trappist-1 system, which we will shorten to Trappy. One astronaut needs to stay with the ship in order to orbit around the parent star while the astronaut descends to Trappy surface. Since we are talking about time, both astronauts will need to carry clocks, which they synchronize before they separate. Far from the surface of the planet, both clocks tick in perfect synchronicity.

One astronaut now descends to the surface of Trappy. On the surface, he is deep in the planets gravitational well, and therefore, experiences a greater gravitational force. The space-time near the planet will also be warped. The effect that the warping has on the astronauts' clock causes it to tick more slowly than the one in orbit. For every tick of the clock on the surface, the orbital clock ticks more rapidly.

On the surface of Trappy, the astronaut does not experience the change in the passage of time because all biological processes are likewise slowed down by the warping of gravity. Just like the ticks of the clock, a distant observer would see the heartbeat of an astronaut on the surface to beat more slowly.

Once the surface mission is complete, the two astronauts rejoin one another in orbit around Trappy. The astronaut who stayed in orbit will be dismayed. She experienced a longer time than the astronaut who was on the surface. Depending on the duration of the stay and the strength of the gravitational field, the astronaut who went down to the planet's surface will experience fewer ticks of the clock, and therefore, be several seconds younger than the one who stayed in orbit.

To calculate how time has worked in a strong gravitational field, the following equation is employed.

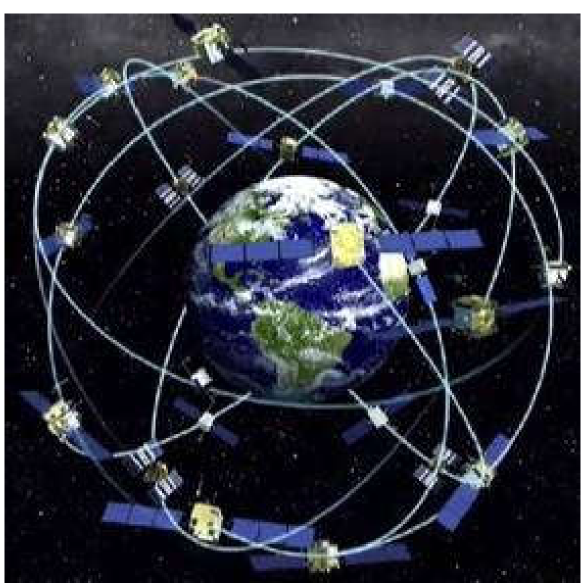
$$\Delta t_{Planet} = \Delta t_{Orbit} * \sqrt{1 - \frac{2GM}{Rc^2}}$$

Equation 16 : Gravitational time dilation

In this formula, the mass and radius refer to the mass and radius of the planet. However, if instead of a planet, you were a distance *R* from a star or a black hole with mass *M*, you could use the same formula. The important thing in this formula is that the quantity inside the square root sign is smaller than one. Therefore, the amount of time that passes when you are in a gravitational well is smaller than if you are out in space far from the gravitating object. Note that this formula does not make sense if the ratio of the mass to radius gets too large. This formula only makes sense if:

$$R > \frac{2GM}{c^2}$$

You might think that your everyday life is not much affected by time dilation due to special or general relativity. However, you may be surprised to learn that almost everyone carries a piece of technology that would be useless without both theories, GPS. The 'Global Positioning System' that you use every time you navigate with a map on your Smartphone depends on Einstein's theory of relativity to function correctly.



Handheld GPS works because the device inside your Smartphone is capable of measuring and comparing the signals from multiple satellites in orbit around the Earth. These satellites are placed in well-known orbits, carrying very precise clocks. By broadcasting, a timing signal that can be noticed a GPS-receiver; the difference in timing signals from different satellites can be used to triangulate your position. Since GPS-satellites travel at about 14,000 $^{km}/_{h}$, they experience a very slight time dilation due to special relativity. Each day, a satellite's clock would appear to slow down by about 7 μs. That does not sound like much, but if you neglected this drift, your GPS would accumulate an error of about 2 km every day.

General relativity predicts that the clocks aboard a GPS-satellite traveling at an altitude of 20,000 km would appear to tick faster than clocks on Earth. Every day, a satellite clock would appear to speed up by 45 μs compared to clocks on Earth's surface. If this error were not corrected, the GPS would accumulate an error of over 13 km a day.

Since special relativity works to slow down the apparent rates of the clock on a GPS-satellite, and general relativity speeds up their apparent rates, the combined effects add up to a 38 $^{\mu s}/_{day}$ error. Without relativity, our GPS devices would drift by over 10 km every day, roughly the same as 12 $^{cm}/_{s}$. Luckily, we know about the effects of relativity. Therefore, we can correct for this drift. GPS devices are some of the most robust tests we have for Einstein's theories of relativity.

In the movie 'Interstellar,' the main character Cooper is sent to retrieve a fellow explorer staff from the surface of Miller's planet orbiting the nearby black hole 'Gargantua.' On the surface of Miller's planet, 1 h of time is equivalent to 7 years on Earth. This is an example of the correct use of an effect called gravitational time dilation.

7.3 Effects Of Gravitational Time Dilation On Time-Dependent Physical Processes

Since gravitational time dilation slows down the passage of time in intensely strong gravitational fields, it equally affects physical processes that are time-dependent. That means that someone observing an astronaut in orbit around the black hole would see their clocks ticking slow, their hearts beating slower, and everything about them slow down.

What happens to a beam of light when it is generated deep in the gravity well near a black hole?

The beam of light experiences gravitational redshift. Recall the Doppler Effect that we discussed earlier. When a moving object like a rocket ship is emitting light, the light can be blueshifted or redshifted depending on the ship's motion towards or away from the observer. If a ship were to accelerate away from you, you would see the light from its engines becoming redder and redder as it accelerated to ever-increasing speeds. Light emitted from deep within gravitational well has to work against gravity in order to leave a planet, or a star, or the region near a black hole. When light travels away from a planet, the photon has to convert kinetic energy into gravitational potential energy. If we remember that red photons have less energy than blue photons, we can predict that the photons emitted from the surface of a star will appear redder to an observer far from the star. This effect is called gravitational redshift. The gravitational redshift effect is very small, but it has been measured in the light emitted by a white dwarf star, and it agrees with the predictions in general relativity.

8 Summary

Earlier in this module, we came to understand how event horizons work by drawing an analogy to a fish falling over waterfall. At a certain point in its descent, the falling fish can no longer communicate with its friend above, because the water is flowing downwards at a greater speed than the speed of sound. Luckily, in the story, we rescued our fishy friend using a rocket pack. This was possible, because the speed of sound is not a universal limit. The speed of light on the other hand is. Were we to drop our fishy friend into a real black hole, a rocket pack would be of little use, because once you are beyond the event horizon of a real black hole, escape is no longer possible. Do not worry; no fish were harmed in the making of this course.

We also learned about a revolution in physics, which began in the early 1900^{s}. Einstein, in a single year and with four extraordinary papers, turned physics on its head. One of the results of these papers was that space and time are no longer absolutes, and in their place was this amalgamation called space-time. In this framework, relative motion is what matters, and many of our traditional notions about how the Universe works no longer apply. Some truly weird things start happening like length contraction, time dilation, and relative simultaneity.

When Einstein went about generalizing his theory of relativity, he realized that there ought to be equivalence between gravitational fields and the acceleration of a reference system. Meaning, if we stuff you in a windowless rocket, you cannot tell the difference between a rocket sitting at rest on the surface of the Earth and a rocket that is accelerating uniformly upwards at a rate equal to the acceleration due to gravity on Earth's surface. Under these two conditions, the two are indistinguishable.

In addition, general relativity comes with its own quirks, one of which being that mass deforms space-time. This is what causes the effect known as gravitational lensing, something not exclusive to black holes, but something they are nonetheless known for, that is their ability to bend light rays.

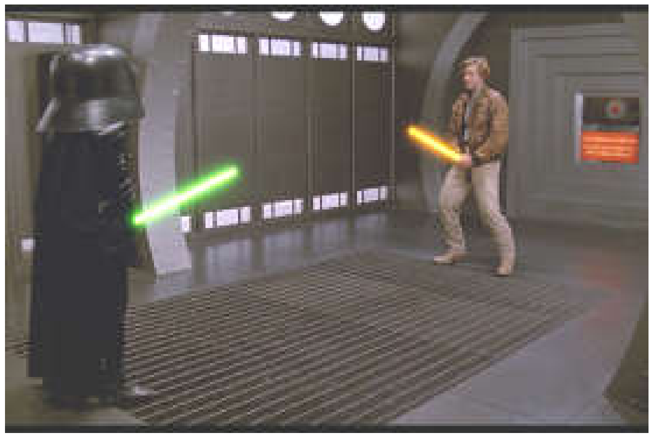
In the next module, we will explore black holes in more detail and learn how to weigh a black hole.

Sizing Up Black Holes

1 Introduction

Black holes represent space-time that is so warped; light itself is unable to climb beyond the event horizon. The properties of a black hole depend on its mass and its spin. Observations of black holes support a categorization system that divides black holes by mass: stellar-mass, intermediate-mass, and supermassive black holes. The black hole categories reflect the environments where the black holes live, and the way these black holes form. Stellar-mass black holes form from the collapse of a star. Less is known about the formation of intermediate and supermassive black holes. The stellar-mass black holes may act as the seeds for larger black holes that grow as other stars and black holes collide and merge. Let us explore the characteristics of each category of black holes.

2 May The Schwarz(schild) Be With You



In the 1987 movie, ‘Spaceballs,’ which is a parody of the ‘Star Wars’ franchise, a mysterious force called the Schwartz allows ‘Dark Helmet’ to battle ‘Lone Star.’ Upon engaging in battle, Dark Helmet says to Lone Star, ‘I see that your Schwartz is as big as mine.’

Strictly speaking, the Schwartz has nothing to do with black holes. However, this scene is an easy way to remember the Schwarzschild radius is a measurement of the size of a black hole. In order to size up a black hole, you need to be able to deduce how massive it is. The first major tool for discovering the properties of black holes was developed by Einstein, who first published his field equation formalism for general relativity in 1915. Einstein himself was not confident that his equations allowed exact solutions. I mean, just look at this mess.

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^A} * T_{\mu\nu}$$

Equation 17 : Einstein's field equation

2.1 Schwarzschild Radius

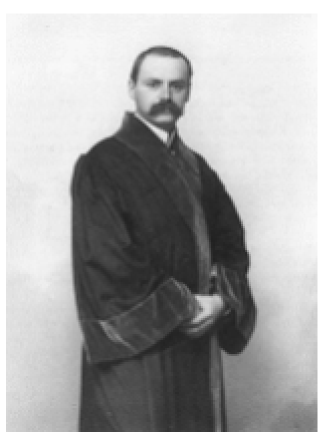


Illustration 78 : Karl Schwarzschild

Well, luckily some people out there do not listen to Einstein. Amazingly, a solution to Einstein's equations was developed by a German astronomer named Karl Schwarzschild the same year that Einstein introduced general relativity. Schwarzschild's solution to Einstein's field equations gives us the first glimpse at the nature of black holes. The result, of course, is the expression for the Schwarzschild radius.

$$R_S = \frac{2GM}{c^2}$$

Equation 18 : Schwarzschild radius

This equation relates the mass of a black hole with the size of its event horizon. The best part, Karl's solution to Einstein's equations was exact, making Einstein extremely happy. At first, it was not recognized that the Schwarzschild solution described black holes. In those early days, they called them gravitationally collapsed objects. Only much later, in 1957, were they formally called black holes. Schwarzschild provided a convenient equation for deducing the radius of a black hole knowing only its mass. However, that still leaves us with a problem. We cannot travel to a black hole to measure the size of its event horizon.

How are we supposed to deduce the mass of a black hole, in the first place?

Karl Schwarzschild was serving in the German army when he wrote the solution in a letter to Einstein in December 1915. Unfortunately, Schwarzschild was suffering from a skin condition and succumbed to it only 6 months later. He died on May 11, 1916 without knowing the impact his work would have in the era of modern physics.

Why then is it so hard to measure the properties of black holes?

Think about it like this! Humans have five senses that we can use to touch, taste, smell, see, and hear objects in our environment. We are really good at it. We can distinguish millions of colors, thousands of smells, hundreds of tastes, etc. There is a reason for the English idiom, 'An illustration is worth a thousand words.' However, black holes have none of these things. They cannot be tasted, smelled; they have no color, they make no sound. Above all, they emit no light.

2.2 No-Hair Theorem

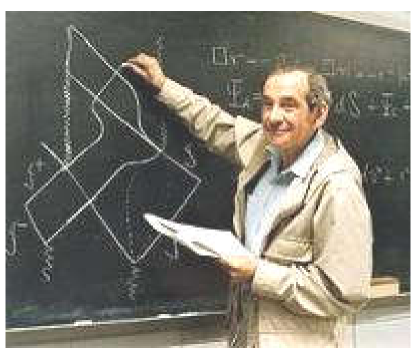


Illustration 79 : Werner Israel

Back in 1967, an astrophysicist named Werner Israel, a professor here at the 'University of Alberta,' was the first to demonstrate why black holes were so elusive. He showed that if any large feature existed on the black hole surface, like mountains or hair, they would tend to smooth out. Scientists now call this the 'no-hair theorem.' The name is used to illustrate that black holes have no other independent characteristics than their mass, charge, and spin. There are no black holes with ponytails, mullets, or Mohawks, because if indeed they had any kind of identifying feature on their event horizon, well, it would be sucked into the black hole.

A black hole's event horizon is a featureless boundary, just like the scene in ‘Spaceballs’ where ‘Dark Helmet’ is searching the desert on the ‘Moon of Vega.’ If you try to comb a black hole, you are not going to find anything.

2.2.1 Law Of Conservation Of Charge

When you rub a balloon against your head, you create a difference in charges between your head and the balloon. Your hair, charged with static electricity, will stand up straight while the balloon can now stick to a nearby wall. A law of physics, called the law of conservation of charge, tells us that charge cannot be created or destroyed. Therefore, even when charges are separated, they are always balanced between + and - charges. Since black holes do not have hair, you cannot rub a balloon against them.

However, a black hole can have charge. This might happen if say, a statically charged balloon is carried across the event horizon, but not the head of hair with the balancing charge. However, there is a force of electrostatic attraction between the + and the -, which, like gravity, will pull these two objects together. This means that any charged black hole will attract the opposite charge, and, eventually, it will become neutral. Most black holes are theorized to be neutrally charged.

The opposite is true for black hole spin. We mostly talk about black holes that have no spin.

What would happen if I throw a Frisbee that is rotating in?

Any of the angular momentum carried by the Frisbee will have to be transferred to the black hole once it crosses the event horizon. A Schwarzschild black hole is a non-spinning black hole, and these types of black holes are not very realistic. Out in space, even a spinning Frisbee is enough to impart spin on a black hole.

We have spent an awful lot of this lesson telling you what you cannot measure about black holes. Now we need to ask what you can measure. Well, a black hole all by itself is not going to tell you everything you want to know. A second object is required, something that is big enough and even bright enough for us to see, which will interact with the black hole, and therefore, reveal its secrets. I am leaving you safe, but before I go, ‘May the Schwarzschild be with you.’

3 Dancing With The Stars

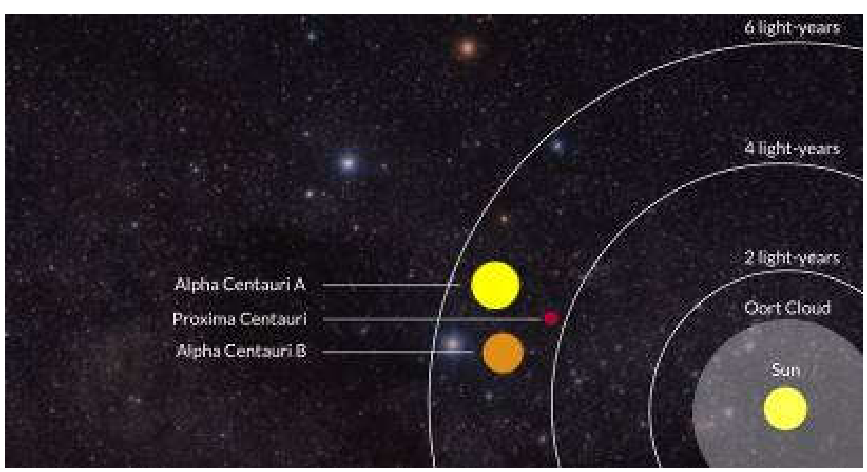


Illustration 80 : Multi-star system

Without hair, black holes are incredibly difficult objects to observe. In order to measure their mass truly, a second object, hopefully one with hair, needs to be near the black hole. Fortunately, most stellar systems contain two or more massive bodies. Our home star, the Sun, is an isolated star. The closest star to us named Proxima Centauri is 4.2 ly away, but many stars including Proxima Centauri live in groups of two, three, or even four stars. In fact, systems consisting of two stars called binaries are just as common as single stars.

3.1 Binary System

Binary systems of two stars can consist of any combination of stars, neutron stars, and black holes. They are scientifically important since they allow us to measure the masses of the components in the system, and in some cases determine their sizes. Since the most accurate method for determining a black hole's mass is to observe its orbital dance with a companion star, we need to examine how stars move when they have a gravitational dance partner.

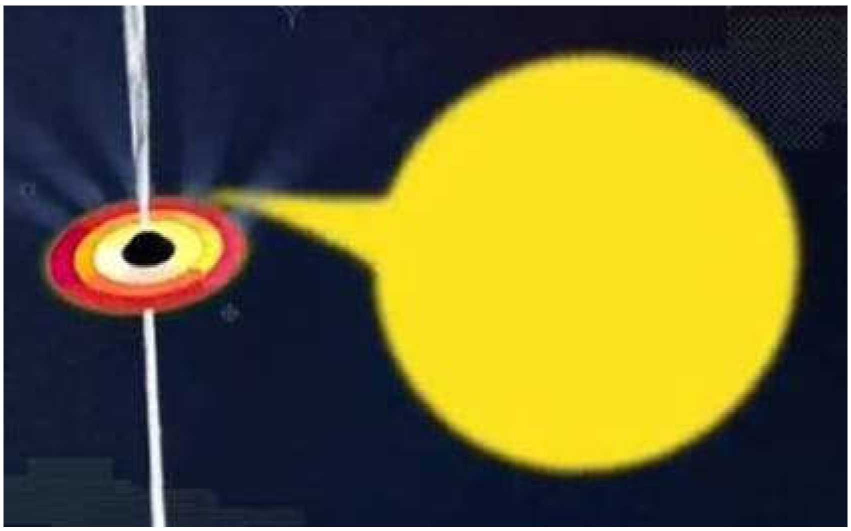


Illustration 81 : Binary system with, possibly, a black hole

When a compact object, either a black hole or a neutron star are in a dance with a companion star, it is sometimes hard to determine what the identity of the compact object is. This is because neutron stars can look strikingly similar to black holes, leading to cases of mistaken identity. The weight of the compact object, or really its mass, is the key difference that distinguishes between these two types of compact objects. Neutron stars cannot be heavier than three times the mass of our Sun, or else they would be dense enough to become a black hole. If we see a compact object hiding in a binary system that might be a black hole, we call it a black hole candidate. If we can measure the mass of the candidate, and it is larger than three times the mass of the Sun, then we are confident that the object is not a neutron star, and we call it a black hole.

3.1.1 Circular Path

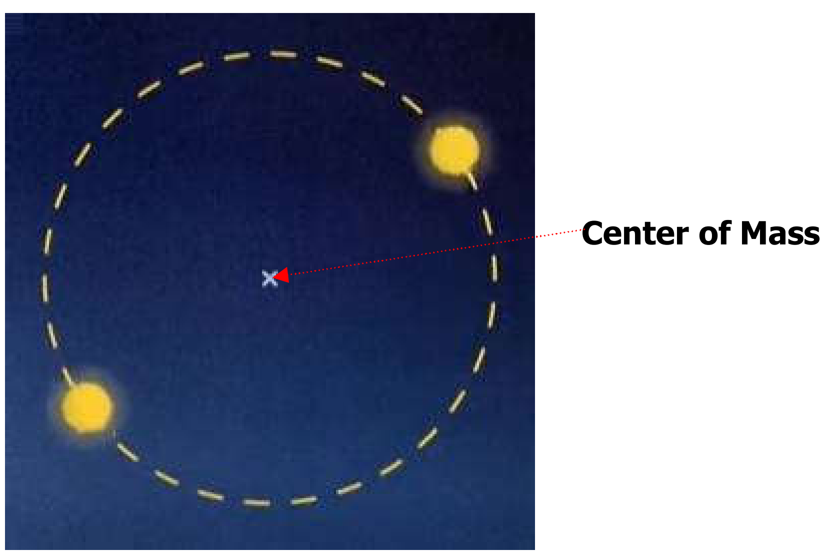
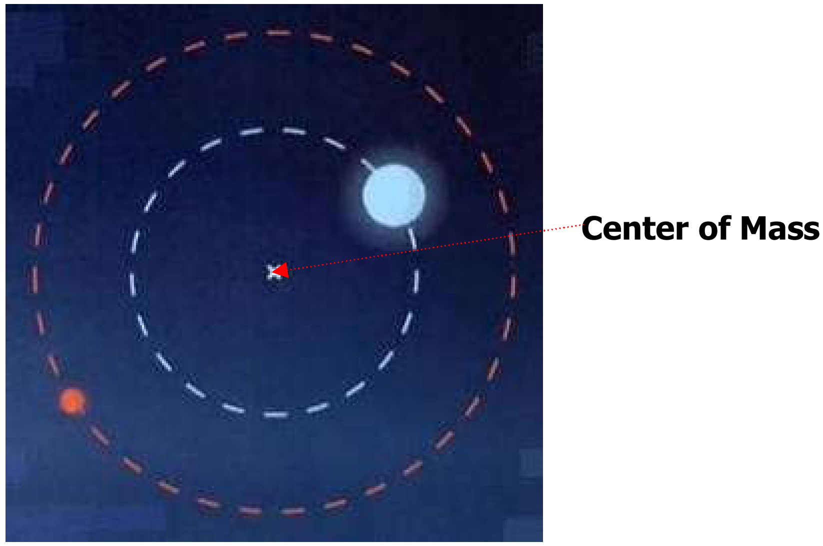


Illustration 82 : Circular path

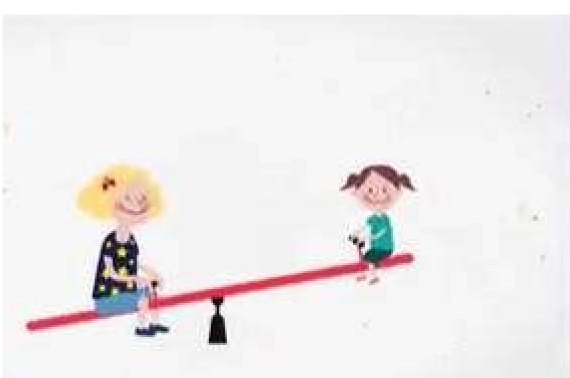
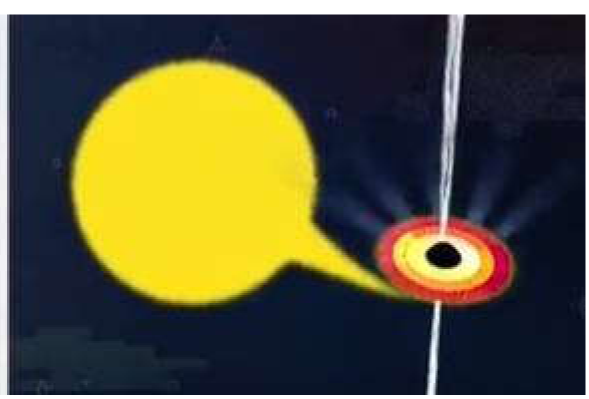
When two stars are in a binary system, they orbit on either circular or elliptical paths around a point in space called the center of mass. Let us start off with circular orbits, with both stars moving in a circle around the center of mass. The center of mass is a balance point that always falls on a line connecting the two stars. If the two stars have the same mass, then the system is perfectly balanced. Notice in this illustration, that the two stars have the same mass and move on the same circular path around the center of mass. The center of mass is always directly in-between the two stars. We call the time that it takes for a star to travel one time around the center of mass the orbital period. Notice that both stars take the same amount of time to make one full orbit.

3.1.2 Elliptical Path

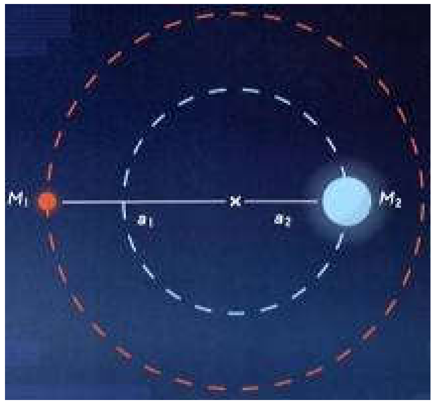


If the two stars in a binary system have different masses, the balance point between them will no longer be equal distance between them. Instead, the higher mass star will be closer to the center of mass while the lower mass star will orbit further away. In this illustration, the high-mass blue star has two times more mass than the little red star. The little red star orbits in a circle with a radius that is two times larger than the radius of the circle that the big blue star orbits on.

The situation is similar to when my little sister and I played together when we were children. My sister is four years younger than I am. Therefore, when I was eight years old, and she was four years old, I weighed two times more than she did. Sometimes we played on a teeter-totter. If we both sat in the seats at equal distances from the pivot point, then the teeter-totter was unbalanced, and I could stay low and keep my sister up high. This led to her crying, which was not really very nice. The only way I could stop her crying was if I moved closer to the pivot point. Once I found the correct balance point, we could then swing up and down and have fun.

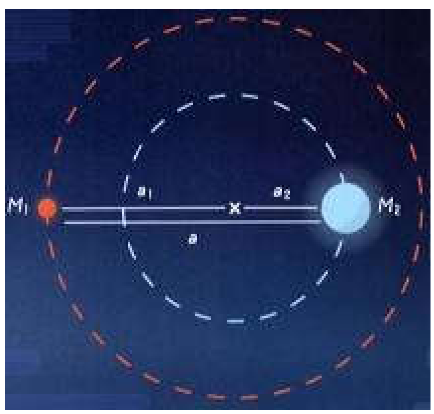
The kids playing on a teeter-totter are similar to two stars in a binary system. The pivot point is like the center of mass. The kids are like the stars, except that the stars move in circles while the kids move up and down. The larger mass kid or star has to be located closer to the center of mass, while the smaller mass kid or star has to be further from the center of mass.



We can quantify the relative distances that the stars have to be from the center of mass in order to balance the binary. The two stars have masses M_1 and M_2. The first star is at a distance a_1 from the center of mass while the second star is located at a distance a_2 from the center of mass. The equation relating the stars masses and locations is:

$$M_1 * a_1 = M_2 * a_2$$

In order to balance the binary, we have to balance the equation, therefore, that the larger mass has the smaller distance from the center of mass. In the above illustration, we can see by eye that a_1 is two times larger than a_2. This tells us that M_2 is two times larger than M_1.



In a circular binary, the total distance between the stars is constant in time as the stars move in their circular orbits. If we define the total distance between the stars to be a, then you can see from the illustration that:

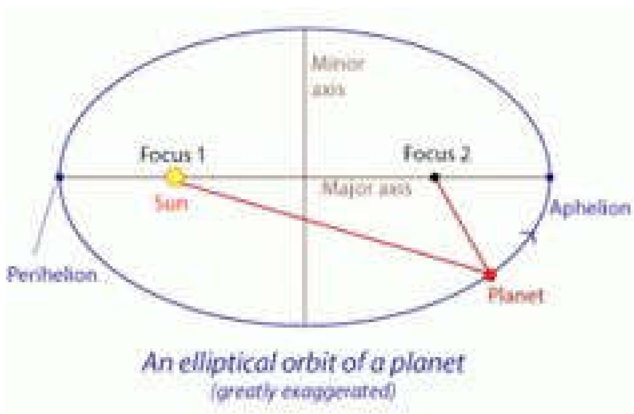
$$a = a_1 + a_2$$

Sometimes a binary star system consists of a bright easy to see star and an invisible star. Even though we cannot see the invisible star, we can deduce its presence when we see the bright star moving in circles around a point in the sky. The empty point in the sky is the center of mass, and the invisible star is also orbiting the same point. The invisible star might be a dim star, like a neutron star, or it could be something that is not really a star like a planet or a black hole. Often we cannot see the orbital motion as circles in the sky, because the stars are too far away. However, what we can do is detect Doppler shifts in the light emitted by the stars. When the star is moving towards us, its light is blue shifted, and when it is moving away from us, the light is red shifted. When we see light from a star periodically Doppler shifting from blue to red to blue, we can deduce that we are observing a binary star system. This is actually the most common way that binaries are detected.

3.2 Kepler’s Laws Of Planetary Motion

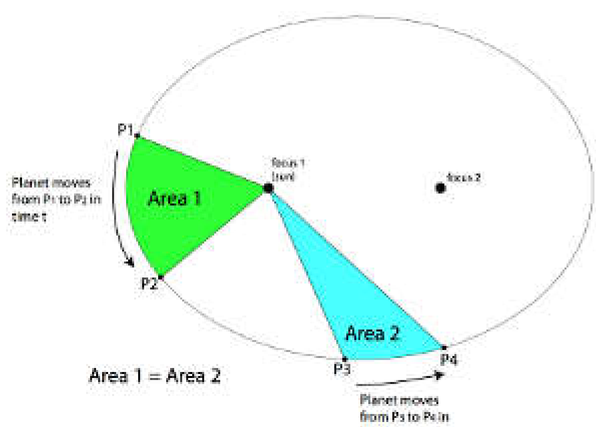
The motion of the planets around the Sun is similar to a binary system. Suppose that we ignored all the planets except for Jupiter, since Jupiter is the biggest planet in our solar system, then the Sun and Jupiter are like a binary system. Since the mass of the Sun is 1,000 times larger than Jupiter, we should not expect that the center of mass be exactly at the center of the Sun. Jupiter is massive enough to pull the center of gravity away from the center of the Sun, somewhere closer to the Sun's surface. Johannes Kepler studied the motion of the planets around the Sun and came up with a set of three laws of planetary motion.

3.2.1 First Law

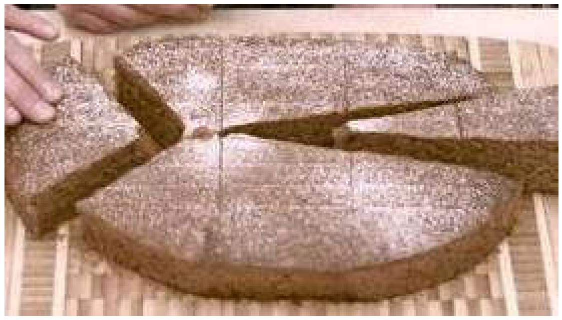


The first law is the law of orbits that states planets orbit the Sun in an ellipse where the Sun is located at one focus. An ellipse is a shape that is sort of like a squashed circle with a short dimension and a long dimension. It has two special points inside that are called the focus points. A circle is a special type of ellipse where both dimensions are the same size, and the two focus points converge to a point at the center of the circle. Although the planets travel on elliptical orbits, these ellipses are almost circular for most of the planets. The Earth's orbit is just a tiny bit elliptical, and the Earth is closest to the Sun in January and furthest from the Sun in July.

3.2.2 Second Law



In a binary star system, Kepler's first law tells us that the stars orbit on ellipses with the center of mass located at one of the focus points. Kepler's second law is the law of equal areas. Imagine a line joining the Sun and the planet. As the planet moves, the line sweeps out an area. Kepler's second law is that the line sweeps out equal areas in equal times.



This is easier to think about in terms of an elliptical chocolate cake. Suppose that we want to cut slices of cake from the focus to the edges of the cake, but everyone should have the same amount of cake. If we cut a wedge near the focus, then we need to cut a wide wedge since the lengths of the cuts are short. If we cut a wedge at the opposite side of the cake, the cuts will be long; therefore, the wedge needs to be skinny. If we cut the cake like this, everyone gets the same amount of cake, and everyone is happy.

Based on the equal areas law, a planet travels faster when is near to the Sun and slower when it is further away from the Sun. Here on Earth, that means that in January, when the Earth is closest to the Sun, the Earth travels faster, and in July, when the Earth is further from the Sun, it travels slower. As a result, the Earth spends more time in the outer parts of its orbit.

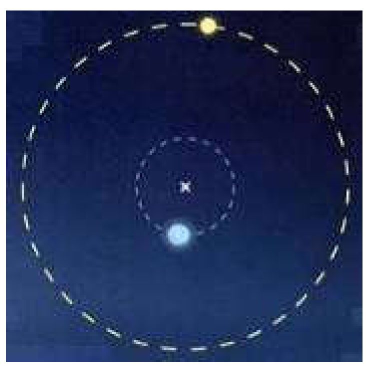
3.2.3 Third Law

Kepler's third law originally only applied to planets, but Newton improved it therefore, that it could be used to describe the orbit of stars in a binary system. Kepler's third law is an equation that relates the masses of the stars to the orbital period and the total distance between the stars. The equation is:

$$M_1 + M_2 = \frac{a^3}{P^2}$$

Equation 19 : Kepler's third law

In this equation, *a* represents the total distance between the stars measured in au, which is the distance between the Earth and the Sun. The time for the stars to orbit around the center of mass, the orbital period, is represented by the letter *P*. The period is measured in units of years. The sum of the masses of the two stars is in units of the Sun's mass. We had better do an example.



Suppose that we observe two stars in a binary, we can easily time how long the orbits are by watching for a while and find that the stars take two years to make one full orbit. Measuring the distance between the two stars is harder to do, but we learned that the distance is for astronomical units. Using Kepler's third law, we can calculate the sum of the masses in the star system to be:

$$\begin{aligned} M_1 + M_2 &= \frac{4^3}{2^2} \\ &= \frac{64}{4} \\ &= \underline{16 M_{Sun}} \end{aligned}$$

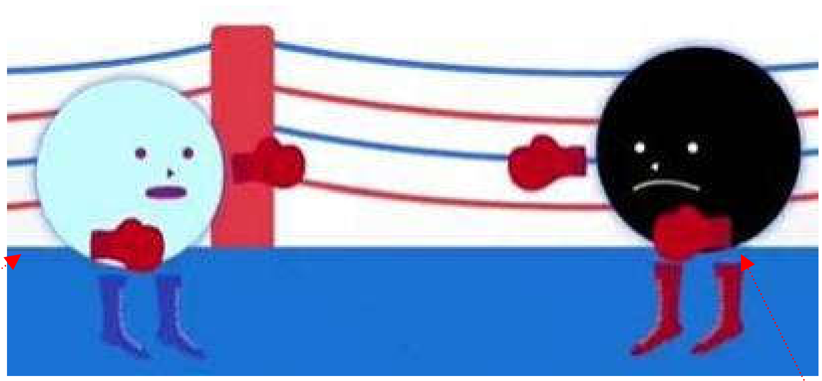
You can probably do this math in your head or use a calculator to find that the sum of the two masses is 16 times larger than the Sun's mass. Unfortunately, this only gives us the value of $M_1 + M_2$. Therefore, we will need some more information to find out the masses of each star as individuals. Perhaps, we can measure the properties of the light from one of the stars, and it is identical to our Sun. Then it would be logical to assume that its mass is the same as the Sun. Therefore, $M_1 = M_{Sun}$, then it is simple to solve for the mass of the other star.

$$\begin{aligned} M_2 &= 16 - 1 \\ &= \underline{15 M_{Sun}} \end{aligned}$$

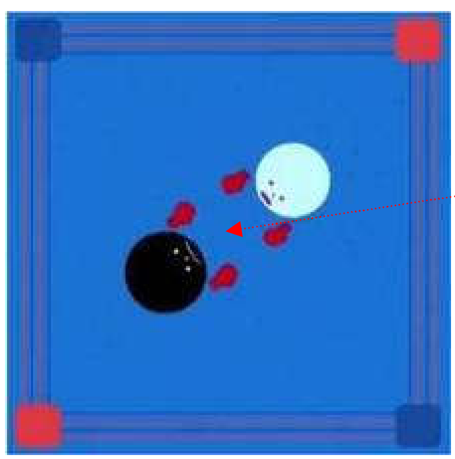
This is a simplified example, but this is how astronomers measure the masses of stars and black holes.

Now that we can finally deduce the mass of a black hole in a binary pair, we can now distinguish between different masses of black holes. Just as sports are often divided into weight classes, so too are black holes lumped into major categories.

4 Weight Training



In this corner of the ring, we have a compact object; let us welcome neutron star. In this corner of the ring, we have a black hole; let us welcome stellar-mass. Three, two, one, orbit.



When a black hole is in a binary system, we are able to deduce how massive it is, but that alone is not enough to say what a black hole really is like. We need to explore the way that black holes are classified. Any black hole astrophysicists will tell you about three basic weight classifications, stellar-mass, intermediate-mass, and super-massive black holes. There are other ways of classifying black holes as well. Like whether they have charge, or spin, but there might be some black holes that do not fit into these categories at all.

4.1 Stellar-Mass Black Holes

Stellar-mass black holes are the lightweights of the black hole family. They are produced at the end stages of a star's life, and range between three solar masses up to about 100. This is due to the 20 - 30 solar mass minimum mass for a dying star that scientists theorize is required to create a black hole. In addition, main sequence stars only get about as big as 100 solar masses. Since stellar-mass black holes require the collapse of a star, they are sometimes called collapsars. During the collapse, lots of gas will be expelled before the black hole forms. The resulting black hole will therefore have a much lower mass than the progenitor star.

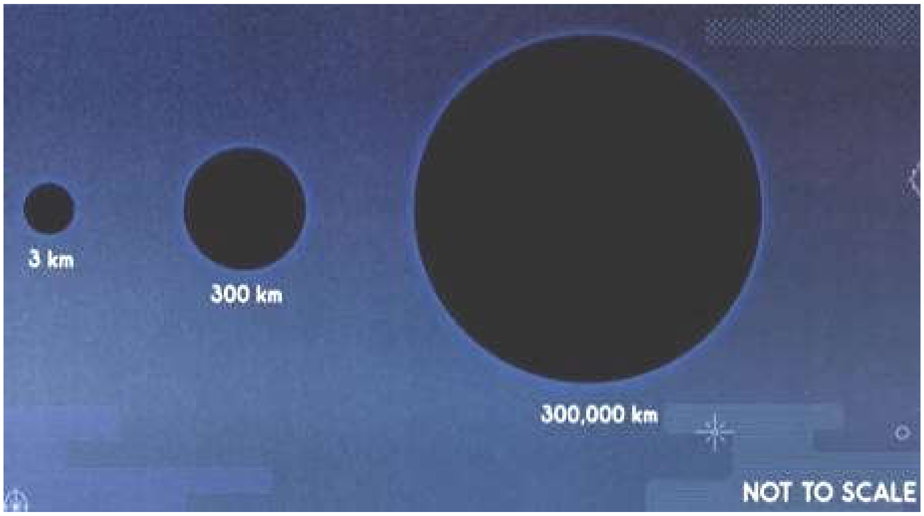
The collapse of a supergiant star might produce a three solar mass black hole. The Schwarzschild radius equation tells us that a three solar mass black hole would have an event horizon roughly 9 km in radius. That is an easy ratio to remember. For every solar mass, the radius of the event horizon gets roughly 3 km larger. A 9 km radius black hole would be about the same height as Mount Everest. Since the diameter is double the radius, a three solar mass black hole would have a diameter of 18 km, which would make its diameter roughly twice the height of Earth's highest mountain Mount Everest. If instead you measure 18 km across the ground, you could walk across a stellar-mass black hole in a little more than 3 h. As long as you could survive the extreme gravity.

4.2 Intermediate-Mass Black Holes

Intermediate-mass black holes are the middleweights of the black hole family. These black holes are not the result of a stellar collapse, but of an existing stellar-mass black hole growing by consuming gas, dust, stars, and other black holes to become more massive. Intermediate-mass black holes are classified in a range of 100 - 100,000 solar masses. At 100 solar masses, the lightest of the intermediate-mass black holes would be roughly 300 km in radius, which means that they would span the orbital height of the 'International Space Station,' which orbits Earth 400 km above the surface.

4.3 Supermassive Black Holes

Supermassive black holes, the heavyweights of the black hole family, occupy everything above a 100,000 solar masses. These are the black holes that reside at the center of galaxies, and are some of the oldest objects in the Universe. Weighing 100,000 solar masses, the diameter of the smallest supermassive black holes event horizon would be about 600,000 km. That is 40 % as big as the Sun. A black hole eclipse would sure looks strange. The biggest black holes that astrophysicists theorize are limited to no heavier than about 50 billion solar masses. That would make the largest mass black holes about 300,000,000,000 km across. At that size, the largest black holes would still be smaller than our own solar system. If you consider that it goes well beyond the orbit of Pluto to the edges of the Oort cloud, which are five quadrillion kilometers from the Sun. A photon traveling at the speed of light would take 58 days to cross a 50 billion solar mass black hole.



We only calculated the smallest black hole in each of the categories in order to illustrate where the boundaries are in the range of sizes. In reality, these boundaries are more like scientific guidelines than they are rules. The black holes that we have observed and measured fall all across this scale. The first black hole merger detected by LIGO created a stellar-mass black hole weighing 60 solar masses. We suspect that intermediate-mass black holes could be found at the center of smaller dwarf galaxies, which can be found in orbit around larger galaxies like the Milky Way. They fall into the intermediate category, but below 10,000 solar masses, they are just below our guidelines for supermassive black holes. The black hole at the center of our galaxy is Sagittarius A. It weighs just over 4,000,000 solar masses, our galaxy's heavyweight contender.

5 Stellar-Mass Black Holes

Stellar-mass black holes are born during the violent deaths of massive stars. If the star in question wandered through space as an isolated star, like our Sun, then the black hole formed as a result of the star's death would also be an isolated black hole. Since isolated black holes wander through space without a companion, they have little to feast upon. As a result, there is little material for them to consume, and therefore, they can be virtually undetectable.

Such isolated black holes can also be formed by a different route. Stars are more generally born in multiples, therefore, as binaries, triplets, or quadruplets, a.s.o. If one of these stars is a high-mass star, it will burn through its fuel more rapidly than the others in its family will. At the end of its life, it will explode in a violent supernova explosion. This explosion can provide a kick that, if strong enough, would break up the family, throwing a black hole out into space by itself. The ejected black hole may even be on a trajectory that throws it out of the disk of its host galaxy.

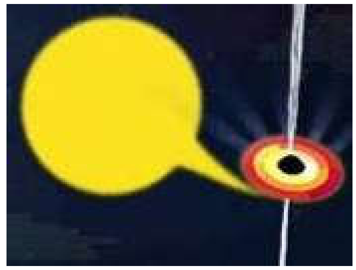


Illustration 83 : Black hole in a binary system

If, however, the kick is small, the binary will remain intact, providing a black hole with a handy food source to munch on for many years to come.

Since stellar-mass black holes are the endpoint of a star's life, they can occur anywhere you would find stars. This means that stellar-mass black holes are found scattered throughout galaxies. They can be seen around the core of a galaxy, or at its outer limits.

5.1 Selection Bias

Almost all of the known stellar-mass black holes have been found in binary systems, but this does not mean that black holes in binaries are more common than isolated black holes. Instead, this is most likely due to selection bias. In science, whenever we choose a sample based on how easy it is to find something, instead of how common it really is, we introduce a bias. This is called selection bias.

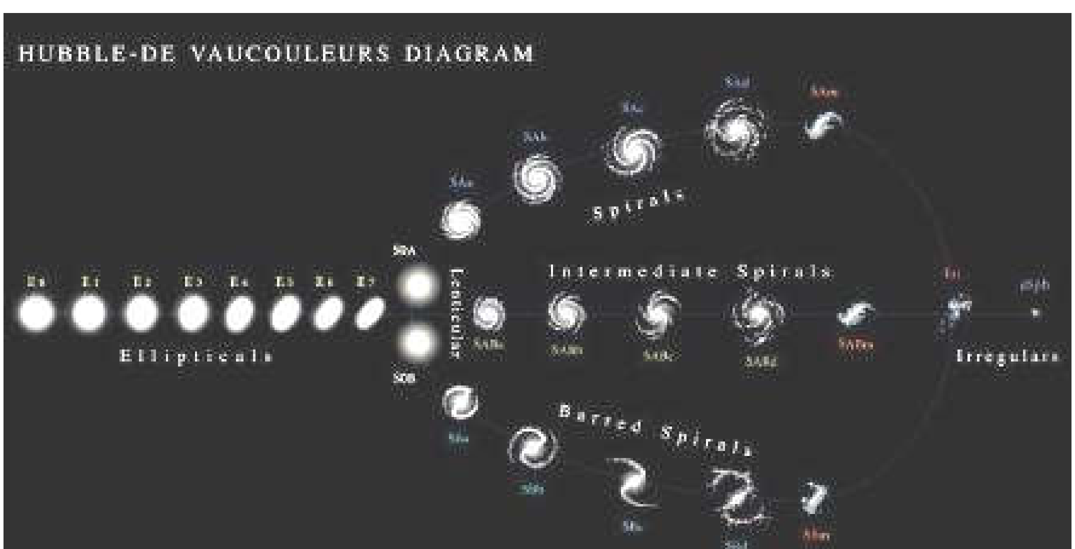
Actively feeding black holes in binaries are much easier to spot than their fasting counterparts. This means that we are much more likely to detect stellar-mass black holes in binaries when we look out at the night sky. Theorists have predicted that it is more likely that black holes will be isolated. The reason is, that there are more ways to make isolated stellar-mass black holes.

Now we know how stellar-mass black holes are born, where to find them, and what they can feed on.

What about other types of black holes? Where can we find a super-massive black hole?

Let us explore that next.

6 Supermassive Black Holes



Supermassive black holes are the largest mass black holes and are found at the centers of galaxies. Galaxies are large collections of stars ranging from small galaxies consisting of hundreds of millions of stars, up to the largest galaxies, which can have upwards of 1 trillion stars. Galaxies fall into several categories developed by astronomers based on their shapes, like spiral galaxies and elliptical galaxies. There are also galaxies that do not fit into the standard classifications. Our classification system has really become a zoo of galaxy types. Among the unusual creatures in the galactic zoo, active galaxies are those, which are thought to host a supermassive black hole at their center. Let us visit the zoo.

6.1 Seyfert Galaxy

Illustration 84 : Seyfert galaxy NGC 7742

The galaxy NGC 7742 is an example of a Seyfert galaxy. Seyfert galaxies are spiral galaxies, with unusually bright central regions. The property of the light emitted from the bright pores is not typical of regular star light. Normally the light from a galaxy is mainly blackbody emission from the stars, as we learned about earlier. However, the central regions of Seyfert galaxies also have a bright emission spectrum, which indicates extremely hot gas. We will learn what an emission spectrum is in a later lesson.

6.2 Quasar

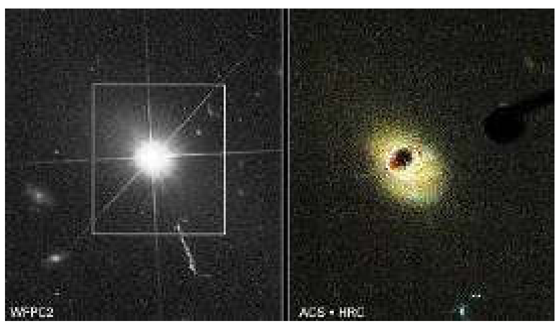


Illustration 85 : Quasar 3C 273 (Hubble image)

The first quasar discovered in 1963, is called 3C 273. In the first pictures taken of the quasar, its features could not be resolved, and it looked much like a star. However, the properties of this star seemed very peculiar; therefore, it was called a quasi-stellar object. This name was later shortened to QSO or quasar. Modern images show that the quasar is not a star, but the ultra bright nucleus of a galaxy. On the left, the quasar is the very bright point of light in the middle of the box. The spikes that are visible are artifacts of how the light is collected by the telescope. You might be able to see faint light from the galaxy surrounding the bright quasar. There is a jet of gas poking down into the right. In order to take a photo on the right; the Hubble space telescope placed a shield over the bright light, which allowed it to take an illustration of the galaxy.

6.3 Blazars

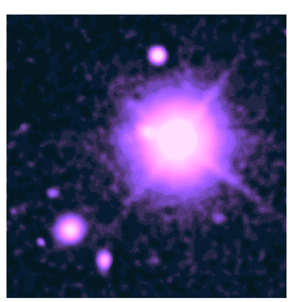


Illustration 86 : BL Lacertae

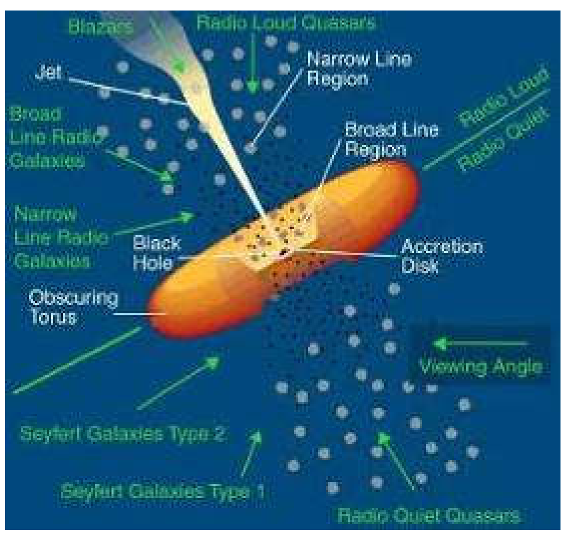
In 1929, astronomers observed a star like object that they called BL Lacertae, or BL Lac for short. This thing also looked like a star through a telescope, but its brightness varied so wildly that it could sometimes be 15 times brighter than it was during the previous month. At the time, it was classified as a variable star, but when better telescopes observed BL Lac, evidence for a galaxy could be seen surrounding the bright point of light. Other similar galaxies have since been discovered, and they have been called BL Lac objects, since they seem very similar to the original. More recently, astronomers have been calling these galaxies BLAZARS. When Blazars are imaged, we find them at the center of elliptical galaxies.

6.4 Radio Galaxies

Illustration 87 : Radio galaxy Centaurus A

Galaxies are made up of lots of stars. Therefore, we expect the light from a galaxy to look like the light from stars. Stars emit most of their light in the UV, Vis, and IR-parts of the electromagnetic spectrum. One thing that stars do not emit in significant amounts of is radio waves. That means that normally we would not detect much radio wave emission from galaxies. However, a small fraction of galaxies emits many radio waves. We call these galaxies radio galaxies. Most radio galaxies are also giant elliptical galaxies.

6.5 Active Galaxies



Active galaxies, that are part of this zoo, share many similar properties. Typically, they have a bright central object called an ‘Active Galactic Nucleus,’ or AGN, which is surrounded by the fainter stars that make up the spiral or elliptical galaxy. Have a look at this diagram, which represents a unified model for all of these active galaxies.

The unified model for an active galactic nucleus has a supermassive black hole at its center, surrounded by a disc of gas that orbits the black hole and emits lots of energy. In some cases, there is a jet of gas shooting out from the central object. We will learn more about discs and jets in a later lesson. The model predicts that when you look directly down the jet you see a blazar. If you look at the jet from an angle so that you can also see into the accretion disk, then you see a radio loud quasar. If you are looking at the edge of the disc so that the inner part of the accretion disc is blocked, you will see a radio galaxy. If there is no jet, then there will be very little radio emission, and you will see a Seyfert galaxy, which is also something that could be called a radio quiet quasar. Therefore, the difference in the names you call a supermassive black hole really just depend on your point of view.

One thing in common with all the active galaxies is that the supermassive black hole at the center is consuming lots of gas enough to power their energy output. The active galaxies are feeding their black holes, which allow the black holes to grow. The supermassive black holes may have started out as large stellar-mass or intermediate-mass black holes many billions of years ago and grew over time. On the other hand, sometimes there is evidence for supermassive black holes, which are not being fed tremendous amounts of gas, like a supermassive black hole at the core of our own galaxy. These black holes are quiet and much harder to detect.

6.6 Sagittarius A*

How massive are these supermassive black holes?

Although we cannot put a black hole on a scale to figure out how much it weighs, we can still measure its mass. Kepler's laws of orbital motion apply to planets, stars, and black holes. If we can find a star orbiting a black hole at the center of a galaxy, then we can determine his mass. The best example is the black hole known as Sagittarius A star or SGR A*, located at the center of our galaxy. It is possible for astronomers to observe stars orbiting in the region within a few light-years of the center of our galaxy. Astronomers have tracked the orbits of these stars for more than 20 years, which can be seen in this video.

At this point, please watch Astro-101_013.mp4

Video 13 : Observation of Sagittarius A*

In this video, the center of our galaxy is marked with a white dot, and the colored circles mark the position of the false colored stars. Over the years, the stars paths trace out ellipses. All stars moves faster when they are closer to the black hole and slower when it is further out. Just as required by Kepler's equal areas law, the stars in this video orbit the invisible point at the center of the galaxy in a manner similar to how the planets orbit our Sun.

We can use Kepler's third law of motion to compute the mass of the invisible object located at the center. The astronomers who measured the mass had to take into account the 3D-nature of the orbits of the stars. The star SO2 takes 15.9 years to make one full orbit. When a star travels on an elliptical orbit, the distance *a*, that appears in Kepler's law, is equal to half of the length of the long axis of the ellipse. In the case of SO2 the value of *a* is 1,000 AU. Kepler's third law for Sagittarius A* is:

$$\begin{aligned} M_{SGRA*} + M_{SO2} &= \frac{a^3}{P^2} \\ &= \frac{1000^3}{15.9^2} \\ &= \underline{4 * 10^6 M_{Sun}} \end{aligned}$$

The mass of SO2 is tiny compared to the mass of Sagittarius A*. Therefore, we can approximate this as the mass of SGR A* is 4,000,000 solar masses. If you compare the distance between SGR A* and the orbiting star to our own solar system, a 1,000 AU would be well beyond the orbit of the planets, extending into the region where comets orbit the Sun. The closest star to us, Proxima Centauri, is 200,000 AU distant. Therefore, this is a gigantic mass packed into a tiny volume of space. Whatever is located at the center of our galaxy cannot be stars, since we would be able to see them if they were there. A black hole is the only plausible way to get such a large mass into a tiny volume.

6.7 M87

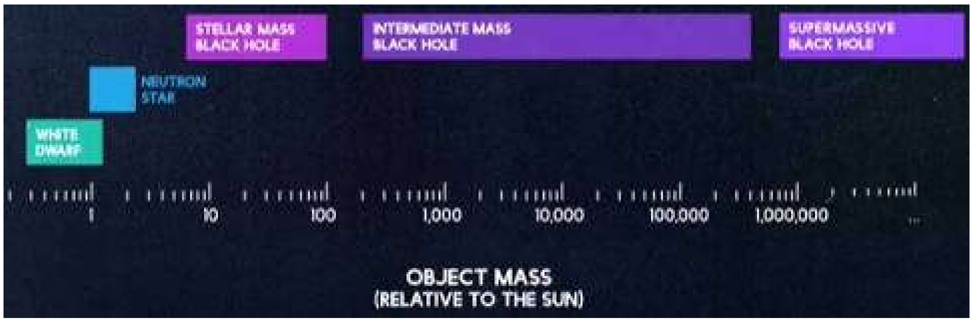
Illustration 88 : M87

Our galaxy's supermassive black hole is actually considered a small fry in the heavyweight division compared to other galaxies central massive black holes. The giant elliptical galaxy M87 has a black hole at its center that is approximately 7,000,000,000 solar masses.

6.8 Dark Matter?

You may have heard the galaxies have dark matter and may be wondering whether the supermassive black holes could be the mysterious dark matter. There are many reasons why supermassive black holes are not galactic dark matter. The most important thing to know is that the mass of a supermassive black hole is just a tiny fraction of the mass of the galaxy inside that it lives. In addition, supermassive black holes are found at the center of a galaxy. The dark matter in galaxies has a mass that is larger than the mass of all the stars in the galaxy and is spread out throughout the whole galaxy in a giant sphere that surrounds the galaxy.

7 Intermediate-Mass Black Holes



So far, we have looked at the extremes of the astrophysical black hole scale, stellar-mass black holes, and supermassive black holes. There is a good reason for this. These extremes are the most well known cases. If we consider all the measured masses of black holes to date, so as of late 2017, we see a cluster of objects in the range of about 5 - 20 solar masses with some reaching as high as possibly 70 - 80 solar masses. These are the stellar-mass black holes. There are also a large number of objects towards the right side of this plot, at the highest mass end. These are the supermassive black holes that are thought to reside in the centers of most galaxies.

Masses have also been obtained for many other low-mass compact objects. These low-mass stellar remnants populate the far left of this plot, and are classified as either neutron stars or white dwarfs. In the middle of this plot, there is a great deal of empty space.

Should there not be something lying in the middle?

This is one of the many questions perplexing astronomers today. If we were to find black holes lying in the center of this plot, they would be known as intermediate-mass black holes. Although the search for these sources is ongoing, intermediate--mass black holes have proven themselves to be very elusive. Intermediate-mass black holes are just that. They have masses that lie between the heaviest stellar-mass black holes and the lightest supermassive black holes, making them intermediate on the mass scale of the astrophysical black holes, hence the name.

What are these objects, how are they made, and why should we care about them?

Intermediate-mass black holes weigh more than 100 solar masses, reaching up to 100,000 solar masses. They are thought to be too big to form from the death of stars that exist in our Universe today.

If this is the case, how are they made?

One theory suggests that these behemoths were formed early in the Universe when it was a much simpler place, chemically speaking that is. The first stars formed when the Universe was only about 100,000,000 y old. At this time, the Universe contained only the simplest elements; therefore, that was just H and He. This early in the Universe, stars could become much larger than they are today, sometimes containing upwards of hundreds of solar masses. We have already learned that massive stars burn hotter, brighter, and quicker than their low-mass counterparts have. This was true for those first stars too. Such huge stars would have very short lives indeed.

7.1 Direct Collapse

We have also seen that massive stars can lose their mass through winds. What we have not yet mentioned though, is that the power of this wind is a function of the stars chemistry. Astronomers have found that the metallicity of a star, or the amount of metals it contains, affect the strength of the stars wind. Here is where I should point out a quirk of astronomy. Forget the high school chemistry class for the moment, according to astronomers the Universe is made up of H, He, and metals. Anything that contains more than two protons is a metal, strange but true in the astronomical circles.

Anyway, back to stellar winds. Therefore, the metallicity of a star or a region give you an indication of how much of these metals are present. When the metallicity is essentially zero, we find that a star loses little to no mass via its wind, irrespective of its size. This means that those first stars would have lost very little mass by the ends of their lives.

At the end of the short life, here is another place where it changes from a life of stars today. Given the huge mass contained in these first stars, astronomers think that they may not have ended in a huge explosion as massive stars do today. Instead, it is thought that once the star ran out of fuel, the force of gravity would be so strong that all of the star would collapse directly down to a black hole. The outer envelope of the star would not be blown away as it is today, it will be dragged down into the black hole to join the core of the star. This stellar death is called direct collapse. This means that the first stars in the Universe may have collapsed to form black holes weighing hundreds of solar masses, they would have created intermediate-mass black holes.

Now that we know a possible direct way to make intermediate-mass black holes, are there ways that are more indirect?

Well, yes. We can make intermediate-mass black holes by combining two smaller stellar-mass black holes. Stellar-mass black holes are the easiest to see when they are actively feeding from that companion star in a binary system. If the companion is a massive star, then it may also create a black hole at the end of its life. If this happens, we would end up with a black hole binary containing two black holes. Over time, these black holes can spiral in, getting closer and closer together until they merge. When that happens, the merging black holes combine to form a single more massive black hole. This is an idea that has been around for a while but recently, has gained traction due to this discovery of black hole mergers with LIGO, the 'Laser Interferometer Gravitational Wave Observatory.' We will be going into more detail about the facilities, such as LIGO, and the physics behind them in a later lesson.

7.2 Runaway Formation

By combining stellar-mass black holes in this way, it is possible to step up the mass scale to intermediate-mass black hole range. For example, if two black holes came together that each wedge in at about 60 solar masses, the result would be a black hole lying in the intermediate-mass black hole range. Some theoretical astronomers have suggested that intermediate-mass black holes could also form by a process known as runaway formation. Runaway formation can only occur in dense regions. Dense regions are areas in space where many stars are clumped closely together, as they are in some stellar clusters. Within the central region of the cluster, you can think of the stars as dances in a club. They are moving around each other as they travel under the influence of gravity. If two of these stars get too close together, they can start orbiting as binaries do, or they can spiral in towards each other and merge. This new star will have more gravity and attract other nearby stars. As they spiral in and merge, the object at the center will have even more gravity, and the cycle will continue, allowing this object to grow and grow until the gravity of this object is so strong that the supermassive star is forced to collapse to make an intermediate-mass black hole.

8 Super Tiny Black Holes

Therefore, that is it. There are only stellar-mass, intermediate, and super-massive black holes. On the other hand, other super-tiny black holes too. The smallest black holes we have observed are all stellar-mass black holes and bigger, but the general theory of relativity does not put a lower limit on how small black holes can be, only on how big stars must be to form them. If there is a different mechanism to form black holes, other than stellar collapse, it might be possible for tiny black holes to exist.

Let us get the Schwarzschild equation out, but this time instead of putting in huge masses like stars, let us see what happens if we try smaller masses, like Earth's. Earth weighs the equivalent of three micro-solar masses, and it has a corresponding Schwarzschild radius of 9 μkm, or 9 mm. That is about the size of a small ball. Imagine that in order to create a black hole with Earth itself, you would need to devise a way to compact the entire planet into a tiny ball this size. I cannot think of any gentle ways of doing that.

What if, instead of calculating the Schwarzschild radius for a massive black hole, we use our own weight in the formula?

I weigh about 75 kg. Therefore, if you calculate the Schwarzschild radius for a mass of 75 kg, my Schwarzschild radius would be $1 * 10^{-25}$ m. That is 10 million times smaller than the classical size of a proton in the nucleus of an atom. Tiny black holes are not anything to worry about.

First of all, we have not actually ever seen a tiny black hole, and we do not know for sure if humans can create them. It may have been possible for small black holes, called primordial black holes, to have been created the moments after the Big Bang, but so far, there is no conclusive evidence of their existence.

Tiny black holes, because of their diminutive size, have a hard time eating. Imagine if you are a tiny 10^{-25} m sized black hole, and you need to try to eat a proton hamburger, that would be the size of the Sun compared to you.

However, there is an even more mysterious reason not to fear small black holes; they evaporate. Do not worry; we will explain more when we begin to talk about quantum mechanics in a later lesson.

9 Summary: Preparing To Explore

Black holes can range in size from many to massive. However, so far astrophysicists have only collected observations from black holes in the stellar-mass and supermassive categories. These are the black holes thought to form from stellar collapse, which then grow by feeding on materials in their environment.

To determine a black hole size, we can use the Schwarzschild equation. However, to do that we must determine a black hole's mass, which requires careful observations of black hole companions. Those companions are the food that black holes feed on, which allows them to grow and progressing to larger and larger masses.

That need not scare you. As we will soon discover, it is much nicer near a super-massive black hole than it would be near a stellar-mass black hole. Moreover, that is important to remember, because the next stage of our journey will take us into the environment around a black hole.

Approaching a Black Hole

1 Journey To A Black Hole

Black holes are a common element in many science fiction movies and TV-shows. In the 2014 movie, 'Interstellar,' the fictional crew of the spacecraft 'Endurance' visits a super-massive black hole called Gargantua. Similarly, in Disney's 1979 film, 'The Black Hole,' the crew of the spaceship 'Cygnus' plunges into a black hole.

Illustration 89 : Cygnus X-1 (CHANDRA image)

In this module, we will approach the nearby stellar-mass black hole, only 6,000 ly away known as Cygnus X-1. From a safe distance, we will make our way towards its event horizon. Along the way, we will make observations, examining some of the major structures that are common in the environment around the black hole. Our journey will finish at the inner edge of the black hole's accretion disk teetering in the closest stable orbit around Cygnus X-1.

In later modules, we will plunge past the inner edge of the black hole's accretion disk to gaze upon Cygnus X-1's event horizon, exploring the latest theories and predictions about what black hole's interior might be like.

Is Cygnus X-1 hiding a wormhole or is there a destructive singularity lurking at its core?

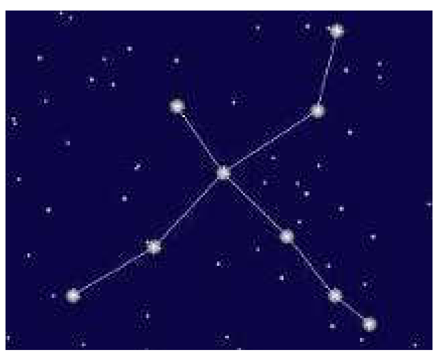
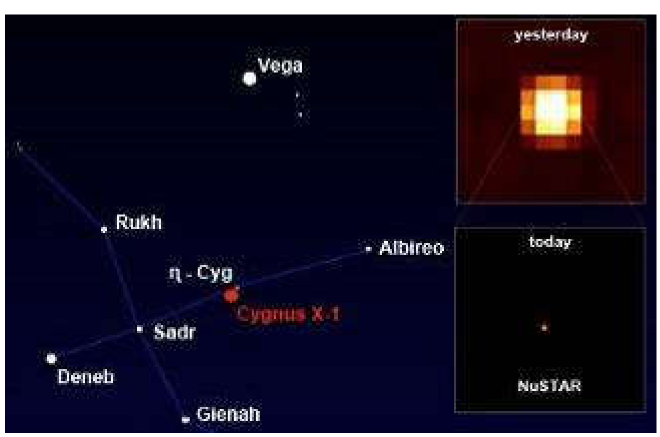


Illustration 90 : Cygnus (Swan)

From our vantage point here on Earth, Cygnus X-1 appears in the constellation of Cygnus, the swan. One of my favorites, because it is visible on summer nights in the Northern hemisphere.



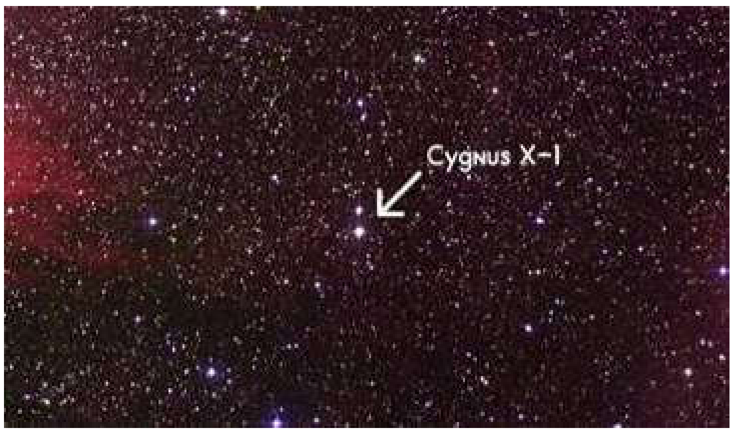
Cygnus X-1 was the first confirmed black hole. Canadian astronomer, Tom Bolton, stated, 'It is inevitable that we should also speculate that this might be a black hole.' Cygnus X-1's status as a black hole was confirmed in 1974. Through a telescope, the stellar companion of Cygnus X-1 is a faint source of light along the neck of the Swan, but a closer X-ray examination of Cygnus X-1 reveals a bright X-ray source originating from the system.

What is creating all of this X-ray light?

Closer to the black hole is a pancake-like feature called the accretion disk. This squashed donut ring of material is the food that is feeding the black hole. As we continue our approach, we will encounter firsthand some of the strange effects produced by the extreme gravity of Cygnus X-1. Friction, tidal forces, and gravitational effects make this journey extremely dangerous.

What dangers can you identify, and how close to a black hole do you think it would be safe for an astronaut to approach?

2 Jets



From a distance, you might expect that there is not much to see when looking at a black hole like Cygnus X-1. However, black holes can be some of the brightest objects in the night sky. This is not due to the black hole itself emitting light, but is an indirect result of the effects the black hole has on the space around it. The bright lights that we see emanating from the regions around black holes are due to the material the black hole is feeding on, and from any material escaping from its mouth.

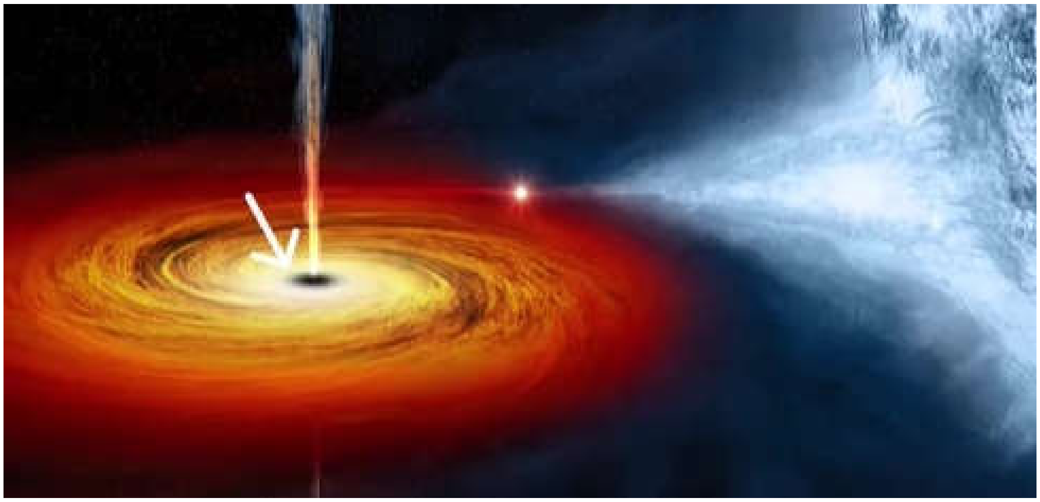
If the black hole's gravity is so strong, how can some of this material escape?

2.1 Astrophysical Jets

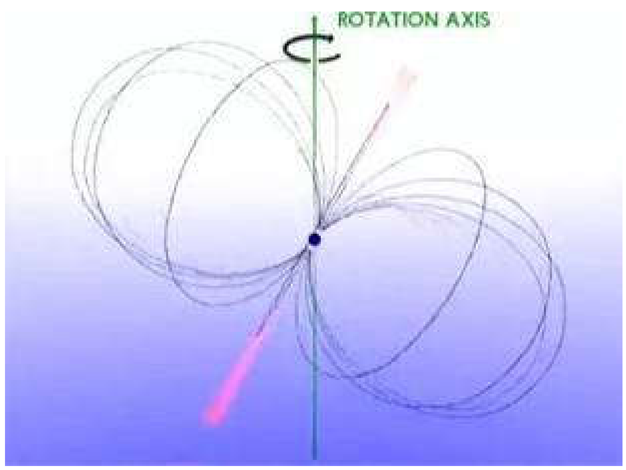
One of the first things we detect from Cygnus X-1 are the radio waves and X-rays being produced from cone-like structures that seem to originate from the area around its rotational axis. These structures are called astrophysical jets, and they are one of the few structures associated with black holes that have been imaged directly. These cone-like structures can funnel material away from the black hole, and in the case of Cygnus X-1, release the power of more than 1,000 suns.

Astrophysical jets are thought to be powered by material falling onto the black hole, or another compact object, but the formation of jets is not yet fully understood. Imagine water cascading over a waterfall. The turbulence at the bottom and the resulting mist are analogous to the way jets are formed. We still do not know what jets are composed of, but leading theories suggest that they are either electrically neutral combinations of electrons, atomic nuclei, and positrons, or a positron-electron plasma. This material is responsible for creating the light that we detect when we see jets.

2.2 Relativistic Jets



Near the inner edge of the accretion disk, hot material interacts with the magnetic fields generated within the disc. Due to these extreme conditions, not only is the material hot enough to be in a state of matter called plasma, but this plasma strongly interacts with magnetic fields to produce light in a process called synchrotron radiation. Although the precise mechanism of the interaction is still unknown, there is no doubt that huge amounts of energy escape from the enfolding material in the form of a jet. In fact, there is so much energy within the escaping material that it can reach 10 % of the speed of light. When this occurs, we say that the jets are relativistic.



Relativistic jets can be seen emanating from compact objects like neutron stars and black holes. The Jets originate at the magnetic poles of the compact objects and are, in general, aligned with the spin axis of the compact object. This is not always the case however, as jets can be slightly offset from the spin axis. The magnetic pulls of the Earth, for example, are offset from the rotational pulls. This slight offset in jets can be observed as a wobble or a lighthouse effect.

2.2.1 Lighthouse Effect

The lighthouse effect occurs as light from the jet sweeps across the field of view. Just like light from a lighthouse sweeps past you as it rotates. While this effect can be seen in any type of compact object, including Cygnus X-1, the lighthouse effect is more commonly associated with a class of neutron stars known as pulsars.

The jets from Cygnus X-1 are 100 times longer than the distance between the Earth and our Sun when imaged in X-rays. On the other hand, if we look at the radio emission from Cygnus X-1, there is evidence that the jets extend even further, possibly 600,000 times the distance between the Earth and our Sun.

2.2.2 Wobble

If a jet is not pointed towards us, the wobble can be seen through other effects. A good example can be seen in the relativistic jet originating from the elliptical galaxy M87. M87 contains one of the largest known supermassive black holes, which powers itself by devouring material at a rate equal to one solar mass every ten years. M87's jet is a jaw dropping 5,000 ly in length, spanning more than 4 % of its host galaxy.

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Video 14 : Wobble in M87 jet

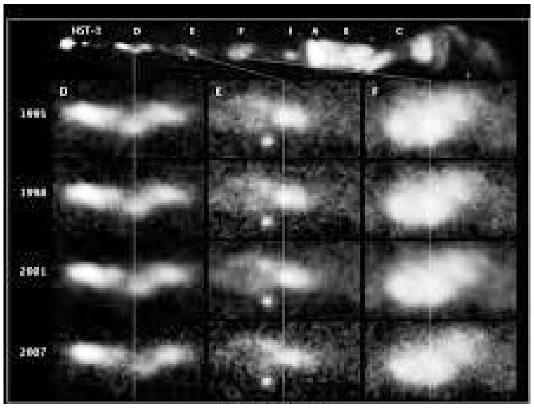
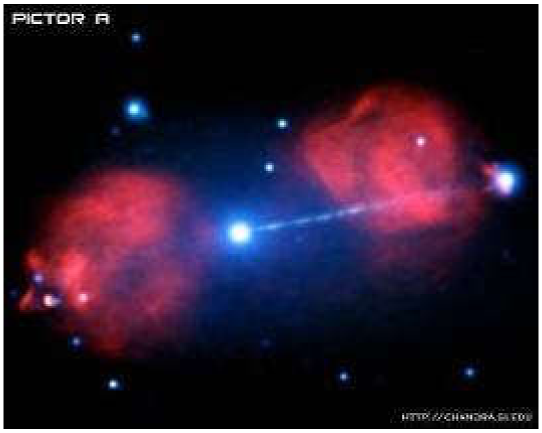


Illustration 91 : M87 jet (Hubble images)

Since the material within a jet is traveling so quickly, we would expect it to have features related to its motion. Indeed, it does. Material from the jets is subject to the same Doppler shifts that we discussed in a further module, which is evidenced by the fact that material traveling away from us appears to be redder and dimmer, versus the brighter and bluer jets that are directed towards us.



A good example of this was a recent survey by NASA's 'CHANDRA Observatory' of Piktor-A galaxy containing a supermassive black hole. NASA calls this black hole 'The Death Star,' because of the powerful beams of energy it generates. This is one of the best images we have of a complete system around a supermassive black hole. In this image, the central black hole of Piktor-A is obscured by an intense X-ray source, depicted by the color blue, which is also the source of the jets. The blue jet that is visible on the right-hand side of the image is pointed roughly towards us, but the counter jet on the other side is pointed away. Due to Doppler shifting, we are not able to see the counter jet.

2.2.3 Radio Lobes

The red clouds are also an important part of the environment around black holes. They are called radio lobes, because they produce significant amounts of radio frequency radiation. We mentioned earlier that the size of the jet in M87 is more than 5,000 ly long. The jets emanating from Piktor-A have been estimated to be 800,000 ly in length, more than 8 times the span of the entire Milky Way. With some jets from black holes exceeding the size of most galaxies, it is safe to say that some jets generated from black holes are among the biggest structures in our Universe.

3 Black Hole Companions

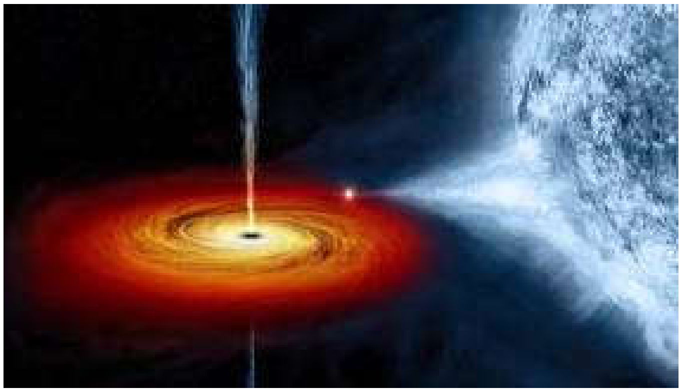


Illustration 92 : Cygnus X-1 with companion HDE 226868

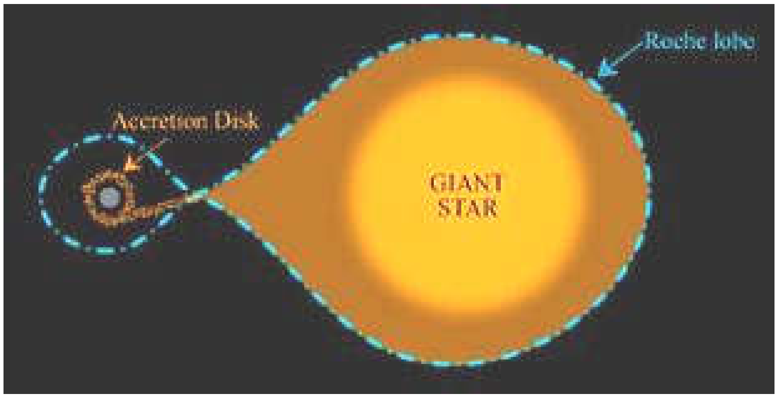
Black holes can have low-mass or high-mass companion stars. The type of companion determines how the mass is transferred. Meaning, how the black hole is fed. High-mass stars generate significant stellar winds, which can transfer large amounts of mass onto the black hole. On the other hand, low-mass stars have much weaker winds. Therefore, in order for them to feed the black hole, they need to be in perilously close proximity. Our black hole binary Cygnus X-1, contains a high-mass star. This companion to Cygnus X-1 is a blue supergiants variable star called HDE 226868, or as I like to call it, lunch. I say this because lunch orbits the central black hole at a measly 0.2 AU, which is half the distance from the Sun to Mercury, and this is a supergiant star.

4 Mass Transfer In Binaries

After examining Cygnus X-1's blue supergiant companion up close, we now shift our view to the black hole and companion star system as a whole. We know these companions can be either high-mass blue stars, like HD 226868, or low-mass stars, like our Sun.

4.1 Roche Lobe

How exactly does a black hole eat from a companion star?



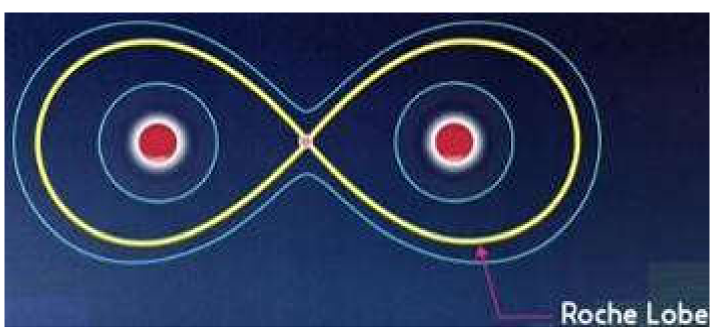
If the black hole is feeding from its companion star, then material from the star must be transferred to the black hole by some mechanism. The answer to this question is explained by the work of a French astronomer named Edouard Roche. He developed a model for the transfer of material between two massive objects such as a star and a black hole known as the Roche lobe. To understand the Roche lobe, let us consider two scenarios, a single star, and a system of two stars. In either scenario, the force of gravity will have some say on whether material will be drawn into the star or will not.

In the case of a single star, if we were to draw lines or contours of constant gravitational potential, we would need to create a series of circles originating from the star. These drawings are similar to the topographical maps of mountains.

How does this change when another star is nearby?

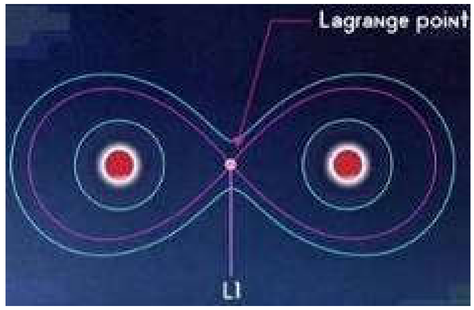
When two stars are in a binary system, the gravity of the two will interact. These two stars would be in orbit around one another, or rather around a common center of mass. However, we must also consider in addition to the gravitational force the force due to the relative motion of the stars, the centrifugal force.

Think about a child's roundabout in a play park. Once you kickoff and begin spinning, you can feel a force pushing you outwards. This is called the centrifugal force. As a result of the rotation of the star system, we have gravity pulling inwards and centrifugal force pushing outwards. It is the combination of these two forces that are represented by the lines of constant potential in binary systems.

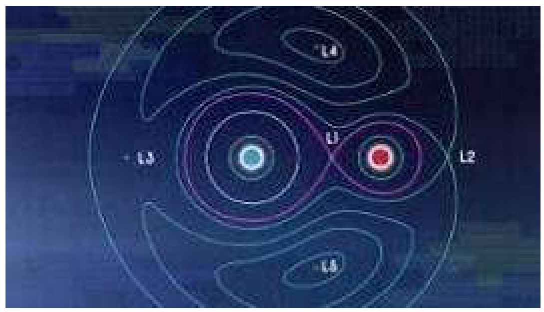


If we now build up lines of equal potential around two stars, we will initially see circles around each of these stars. However, as these rings get larger and closer together, their shape begins to change. They are slowly stretched in the direction of the opposing star. The circles begin to morph into teardrops. This stretch or distortion increases until they connect forming a figure of eight around the two objects. Each of these teardrops or lobes is called a Roche lobe. It is the Roche lobe for the star it contains. Any material that is inside the lobe is gravitationally bound to that star. You can think about gravitational lobes like two lakes occupying adjacent valleys separated by mountains. The lakes watersheds do not share any water unless they fill to mutual height, which we typically call a watershed divide.

4.2 Lagrange Points



Similarly, material within a Roche lobe is bound unless there is a point where the potential is equal between the two stars. The point where these teardrops meet is known as the Lagrange point. The first Lagrange point is commonly labeled L1. If you are an astronaut situated in L1, you would feel an equal gravitational pull towards each of these stars, but there are other points where we could feel the equal pull between the two stars.



If we continue to map the lines of equal potential, we find other Lagrange points. As you can see, there are four other points that surround a binary system. Although we have used an example of two stars, you can draw similar lines of constant potential around any other pair of massive bodies, including the Sun and the Earth, but more importantly between a black hole and its stellar lunch.

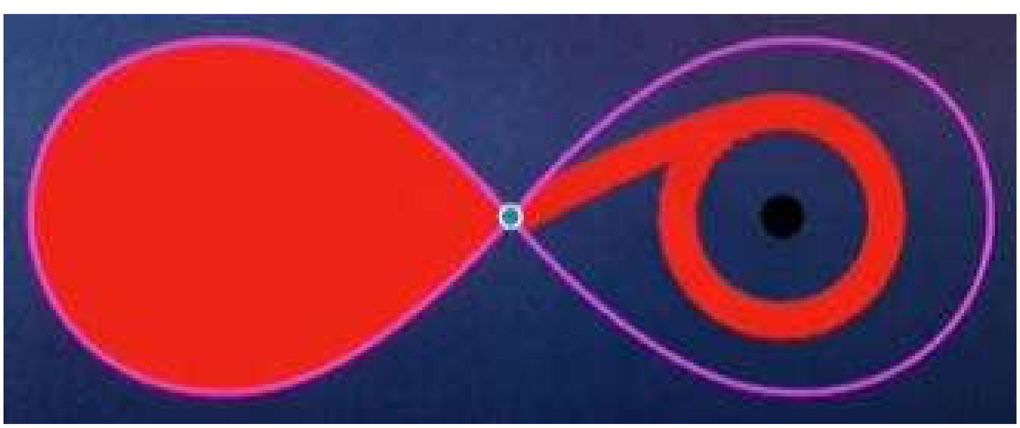
Lagrange points are special regions in space where the gravitational potential is relatively flat making it easy for spacecraft to hover there. Considering the Earth-Sun system, the first Lagrange point lies on their connecting line. This region known as L1 is used extensively as a parking spot for telescopes since they can hover at L1 using small amounts of fuel. As such, this location has been used as a prime spot for astrophysical observations, which we will discuss further in future lessons.

Black hole binaries are a type of system, which contains two massive bodies, and therefore, these systems also have Roche lobes and Lagrange points.

How does this help us understand the transfer of matter?

The transfer of material from a star to a black hole is a gravitational effect.

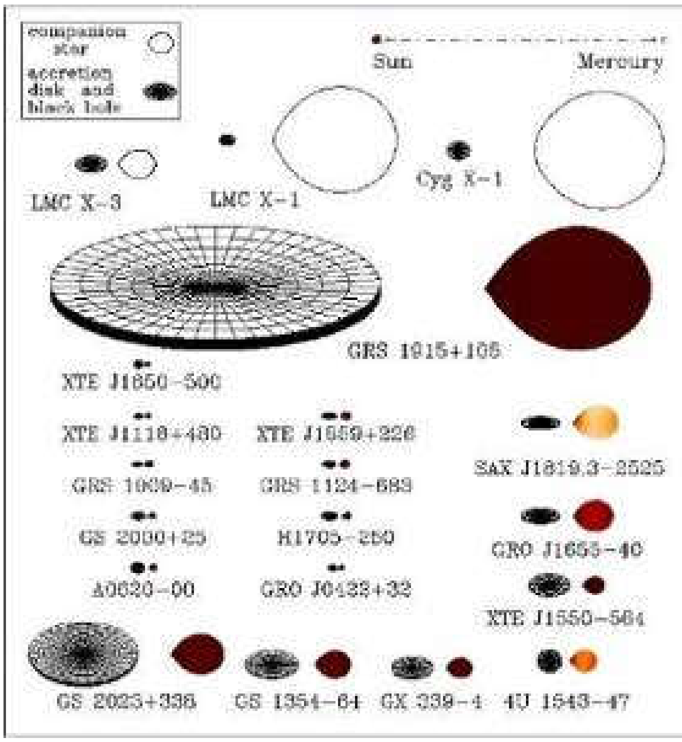
If material from the star moves outside its Roche lobe, gravity can pull it towards the black hole instead, but if material inside its Roche lobe is gravitationally bound to the star, then how can it move outside the boundary?



The easiest way for this to happen is if the star begins to fill its Roche lobe. As stars like our Sun get older, they will swell up to become red giants. At this time, the star can grow to fill its Roche lobe. At that point, material can spill over across the boundary at L1. The star stuff will end stop falling towards the black hole. Stars can also fill lab Roche lobe if the Roche lobe shrinks.

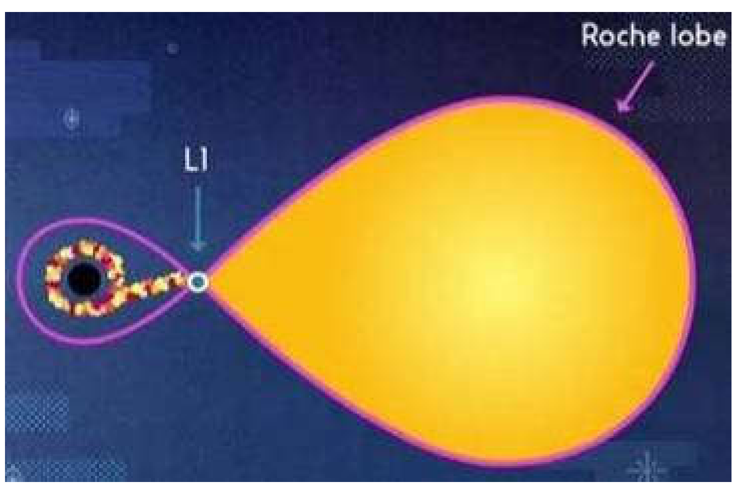
How can this happen?

The Roche lobes would get smaller if the bodies in the system move closer to each other, or as astronomers call it, the binary becomes more compact.



There are many ways that binary systems can become compact. One method involving gravitational radiation will be discussed in a later lesson. This image shows black hole binaries that all live in our galaxy. At the top of the image, you can see our Sun and the distance between it and the planet Mercury. Mercury orbits the Sun at just over a third the distance between our Sun and the Earth. Yet most of these systems are much smaller or much more compact.

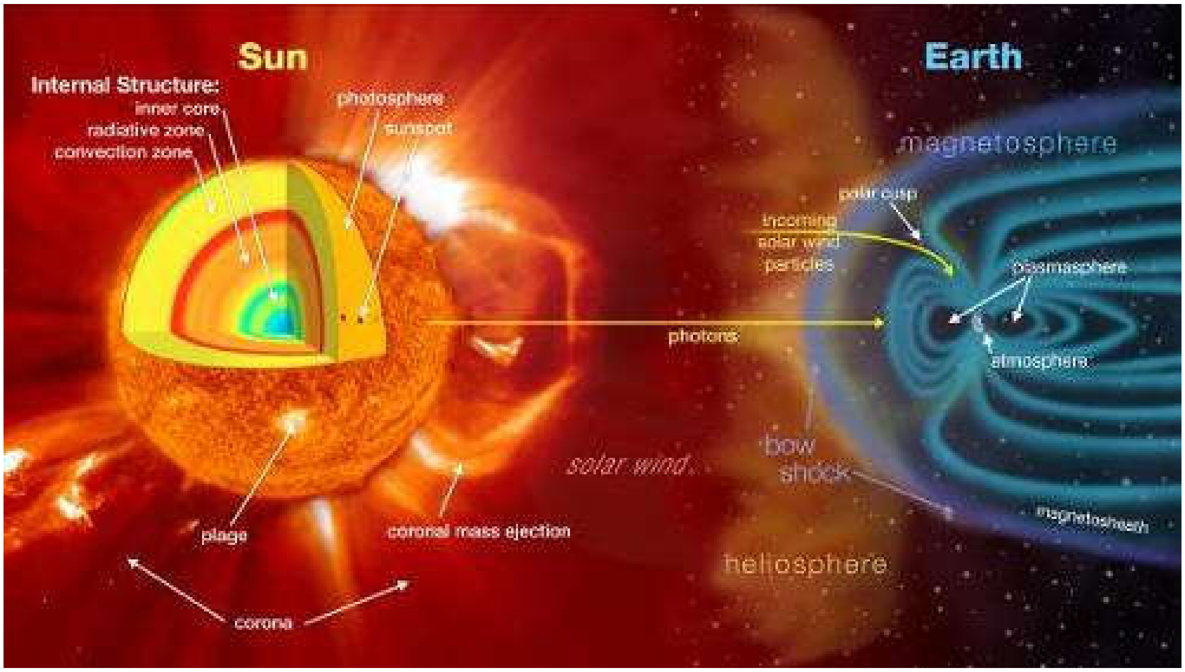
4.3 Roche Lobe Overflow



So far, we have looked at material being stripped away from the surface of the star as it over falls its Roche lobe. This material then crosses the first Lagrange point L1 and starts falling towards the black hole. This process is known as Roche Lobe overflow. It can provide a fairly stable way of feeding a black hole for quite some time.

Is it the only way to transfer mass from the star to the black hole?

4.4 Wind Fed



No. There is another option. Many stars have winds. Our Sun does, but its winds are considered puny by stellar standards. Massive blue stars can blow away up to 100,000,000 times more mass than our own Sun does. Such strong winds can be captured by the gravity of the black hole and fall in towards the event horizon. This type of accretion is known as wind fed.

While wind fed mass transfer is only really an option for high-mass stars, Roche lobe overflow can occur with any type of star as long as the companion star fills its Roche lobe. Our good friend Cygnus X-1 is one such system with a high-mass companion that is both overflowing its Roche lobe and feeding the black hole with high velocity stellar winds.

5 Have A Corona!

Now the material is streaming off the black hole companion, we can monitor material as it progresses closer and closer towards the black hole.

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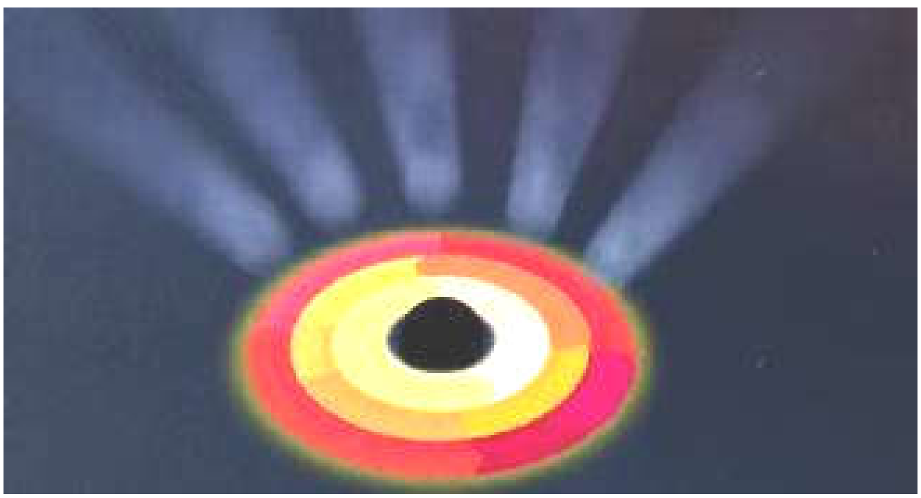
Video 15 : Model of material transfer between two stars



Although this is a simulation of an interaction between two stars, the same physics apply to all black hole binaries. Looking more closely at the material spiraling in, we see a dim cloud-like feature around the black hole in the inner disc. This is the black hole's corona. Astronomers have detected evidence that the corona is a cloud of fast-moving electrons that hang out near the black hole, and they think that coronas come in two flavors.

5.1 Lamp-Post Model Versus Sandwich Model

The first flavor called the lamp-post model explains the corona as a source of light that sits close to the rotational poles of the black hole. The second model deliciously called the sandwich model, explains the corona as a larger cloud that envelops the central disc. Think of it like this, a corona is like two halves of the bagel surrounding the accretion disk of Nutella.

In this artist's rendering, the corona is a diffuse purple light enveloping the black hole. The corona is thought being powered by intense interactions between the chaotic magnetic fields generated by the material falling onto the black hole, and the resulting hot plasma.

The black hole in this artist's rendering is located in the center of the galaxy Markarian 335, in the direction of the constellation Pegasus. Observations of the supermassive black hole have revealed powerful coronal outbursts that accelerate materials nearly 20 % of the speed of light. However, we would like to emphasize that scientists are still in the very early stages of understanding the environment near the black hole. The research into the corona of black holes is ongoing.

6 What Is Accretion?

We have encountered the word accretion several times now.

What exactly does it mean?

In astrophysics, accretion is the word used to describe the process of gas and dust being collected together by gravitational forces. Accretion can happen on many different scales. For example, in the early history of our solar system, gravity caused small particles of gas and dust to collect and combine into larger and larger objects. Eventually growing from tiny greens of dust into planetesimals, and finally into the planets that we know today.

Accretion is also responsible for gathering clouds of H into stars and stars into galactic disks. However, most importantly for this course, accretion is the process by which black holes are fed.

6.1 Viscosity

When a star or a cloud of material is near a black hole, it experiences the gravitational effects. The force of attraction accelerates material towards the black hole, and since particles in the cloud are free to move around, they experience a force called viscosity, the effect of friction during collisions with neighboring particles. Viscosity does two things within the accretion disk. First, it slows the particles down in their orbit, allowing them to fall further into the gravitational well. Second, it heats up the particles, which in turn causes them to glow red-hot; a process that creates light called black body radiation. Much of this energy is derived from the gravitational potential energy of the materials, which we talked about in a further lesson when we discussed escape velocity.

Accretion is not as simple as it seems.

Why are moons, planets, and stars, which are all created by accretion process, are spherical, instead of disk-shaped like the rings of Saturn or the disk of a galaxy?

6.2 Angular Momentum

The answer has to do with angular momentum. Now you are probably already familiar with the concept of linear momentum, which is the product of an object's mass and its velocity. Momentum in this sense is a conserved quantity. Another way of describing it is through Newton's first law of motion; an object in motion stays in motion precisely because it has momentum.

What if an object is not moving a long path, but instead it is spinning in place?

In that case, we now have another conserved quantity, this time called angular momentum. Angular momentum is the product of an object's mass, its velocity, and the distance from the origin around the spin. Usually physicist tidy this up by saying angular momentum is the sum total of all the masses being considered and their distances from the origin into a neat quantity called the moment of inertia. In this way, angular momentum can be expressed in a similar way to linear momentum:

$$\begin{aligned} L &= I\omega \\ L &= \text{Angular Momentum} \\ I &= \text{Moment of Inertia} \\ \omega &= \text{Angular velocity} \end{aligned}$$

Equation 20 : Angular momentum

What is important here is not the form of the equation, but rather the statement that angular momentum is a conserved quantity. In plain language, an object, which is spinning, will continue to spin. Now here is what I mean.

At this point, please watch Astro-101_016.mp4

Video 16 : Demonstration of angular momentum

As our subject pulled his arms in, he started to rotate faster. He was conserving angular momentum. As you will see shortly, the exact same thing happens to the material in an accretion disk when it goes into smaller and smaller orbits.

However, were we not supposed to be talking about disks versus spheres? What does angular momentum have to do with that?

If a structure is accreting out of a rotating cloud, the angular momentum will dictate in which direction and how fast the final object will spin. Suppose we started with a nice big nebula, and we wanted to condense a star out of it. From a distance, it probably does not look like the nebula has much angular momentum, but it does, because all of the particles are far from the center, they have a huge momentum inertia. As these particles collapsed due to gravity, they must rotate faster and faster in order to conserve angular momentum. Now since the material in a nebula began with some amount of angular momentum, the new smaller structure must preserve the original amount by rotating faster.

6.3 Oblate Spheroid

Why then is the Earth spherical instead of flat?

For structures like Earth, which are solid objects held together by their own gravity, the centrifugal force does flatten it a little bit! Which is why we call Earth an oblate spheroid instead of just a sphere. If Earth were to rotate faster and faster, eventually the centrifugal forces will exceed the internal stress, and Earth would be torn apart. Angular momentum causes rotating objects to flatten into disks.

Earlier, we said that accretion was the process by which black holes were fed. Now when a physicist says that, we are feeding a black hole, we are describing the transfer of material and energy towards the black hole's event horizon, in the same way that, when you are eating, you are transferring material and energy into your own body's mouth horizon.

When we were discussing Newtonian mechanics in a further lesson, we used two equations to describe two important types of energy: gravitational potential energy and kinetic energy. Any matter in a gravitational field has potential energy, which it can give up as it descends into the gravitational well by converting potential energy into kinetic energy.

Let us have a look at some matter falling into a black hole. Recall for a black hole that the gravitational potential of energy for the infalling particle is:

$$E_{potential} = \frac{GMm}{R}$$

If the particle starts with zero velocity, somewhere infinitely far from a black hole, much of the gravitational potential energy will turn into kinetic energy.

In which case we set kinetic energy $\frac{1}{2}mv^2 = \frac{GMm}{R}$?

6.4 Eddington Limit

Since the mass M of a black hole can be large, and the radius can be minuscule, even the tiniest particles can be accelerated to incredible speeds. However, it is worth noting that these equations are classical. All of the energy of the infalling particle has to go somewhere, and indeed, much of that energy becomes heat, which is then radiated away in the form of light. In the center most regions of the accretion disks around black holes, the disk material can become so incredibly hot that it produces enough light to push back against infalling material. Here, we use a specific name for when the force of gravity, pulling material inward is equal to the pressure pushing material outward. It is called the Eddington limit, named after Sir Arthur Eddington.

The Eddington limit describes a natural limit to how much material can be captured from the accretion disk around a black hole. This is based on its power output, or luminosity, of the infalling material. The limit is expressed in this equation.

$$L_{Edd} = \frac{4 * \pi * G * M * m_P * c}{\sigma_T}$$

Equation 21 : Eddington limit

If the luminosity of the disk exceeds the Eddington limit, material in the disk will be pushed outwards from the interior of the disk. If the luminosity is below the limit, gravity will pull more material in. This equation is powerful, because it allows scientists to estimate the minimum mass that a black hole must be simply by measuring the luminosity of the system.

7 Spinning Through The Disc

Now let us consider what it would be like to be a little piece of dust in the accretion disk around a black hole. Since our piece of dust is in orbit, along with all the other little pieces of dust, we say that it has both angular momentum, which prevents it from falling further inward, and gravitational potential, which is trying to pull it further inward.

How can these particles migrate through the disk?

Well, on their own they cannot.

What do we know so far?

For one, we know that due to Kepler's laws that the orbital speed of a piece of dust is related to the distance it is from a central object. When a dust particle is far away from a central object, its orbital speed is low, but when it is close to the central object, the orbital speed is high.

To understand what is happening really, we need a second piece of dust. Let us say that our first piece of dust, dust *A* in the accretion disk around the black hole is sitting at distance *a*. Now let us consider dust *A*'s friend, dust *B*, is a little further away, but not too far from the central black hole. Since dust *A* is closer, it will be moving a little faster, and since dust *B* is further, it will be traveling a little slower. Every once in a while, dust *A* will catch up and bump into dust *B*.

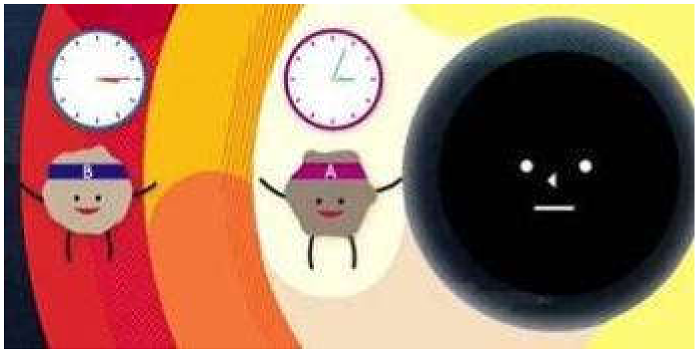
What this does is it causes dust *A* to slow down and dust *B* to speed up. The result is that the slower dust *A* will fall further into the disk gaining kinetic energy, and dust *B* will use its little speed boost to find a stable orbit further away from the black hole gaining potential energy.

In an ideal case, we are not losing any energy, but reality is far from ideal, which means that both dust *A* and dust *B* will be slightly hotter than they were before the collision, and that heat can be carried out of the disk by thermal radiation, which is how we see them. As energy is being carried away from the system, material in the disk will be pulled further inwards.

In a real disk, there are countless dust particles participating in these collisions. Therefore, instead of looking at individual collision, scientists often consider the physics of a large number of interactions. Material moves inward through the disk by losing energy through a viscous force. This process turns the gravitational potential energy of the disk into heat, which is then carried away by radiation allowing more material to feed into the black hole.

7.1 Gravitational Time Dilation

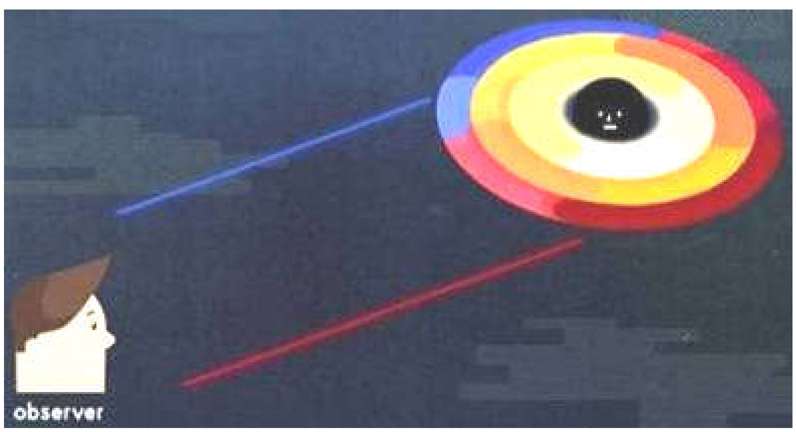
Until now, we have not really considered what effects the black hole has on the accretion disk other than gravity obviously. Now we shall briefly discuss how gravitational time dilation, gravitational red shift, and the Doppler Effect have on the properties of the disk. Our friendly little dust particles that were exchanging energies were also aging at different rates.



If each of dust *A* and dust *B* were carrying tiny dust clocks with them, they would tick at different speeds. Clock *A*, being close to the black hole, would appear to a distant observer to tick more slowly compared to clock *B*, which is further out in the disk. Practically what this means is that if you wanted to time travel into the future, all you would need to do is get very close to a black hole for a small amount of time. In that way, the clocks in the rest frame of the Universe would appear to tick faster, and you would reemerge from near the black hole into a time-shifted future.

7.2 Gravitational Redshift

Astrophysicists need to account for gravitational time dilation when they are accounting for the rates that particles emit radiation. A hot particle, for example, emitting radiation near a black hole would appear to be radiating at a much slower rate. On top of that, due to gravitational redshift, the light being emitted from the accretion disc close to the black hole will lose energy as it climbs out of the black holes gravitational well, thereby becoming red shifted from its original wavelength.



However, wait; there is still more. Due to the rotation of the accretion disk, observers will also measure a difference in the intensity and wavelength of light depending on whether material in the accretion disk is approaching or moving away from the observer. For a spinning disk, the material moving away will be dimmer and redder, whereas the material moving towards will be brighter and bluer.

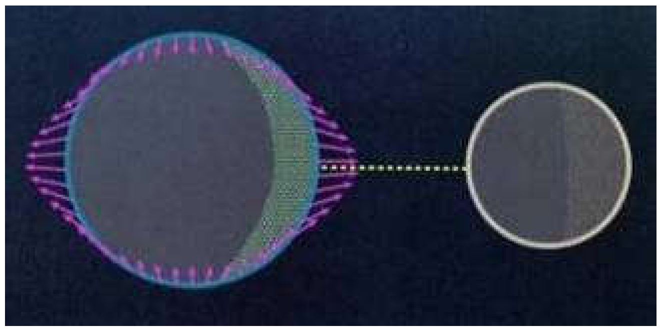
In order to understand black holes truly, each of these effects along with many more need to be taken into account. Talk about a fun puzzle for theoretical physicists.

7.3 Tidal Forces

Now that we have a good grasp on what we would see in the environment around a black hole, we should now ask what an observer would feel in the environment around the black hole. Normally when we think of a spacecraft in orbit around Earth, we imagine an astronaut experiencing the sensation of weightlessness. With gravity, only serving to keep them from being flung out into deep space, but there is another effect that becomes significant around black holes that will be noticeable to an astronaut nearby; tidal forces.

Illustration 93 : Bay of Fundy in Canada

Tidal forces are named after the tides here on Earth, which we experience as the rise and fall of sea levels that occurs periodically. Humans have speculated about the cause of tides for millennia, and today we know that they are caused by a combination of the gravitational forces of the Moon and the Sun gently pulling on the water in the ocean, or rather tidal forces act on everything on Earth, but it is really only the oceans that we notice.



For a simple spherical object, gravity acts to pull the objects towards the center of mass. However, when a second gravitational body is introduced, the forces are now the sum of the gravitational forces due to both of the bodies. This presents an interesting dilemma. Since the gravity from the second body changes strength with distance, and thus the tidal forces will have a different value and direction over the surface of the first, these tiny differences in gravitational forces are all that are needed for an object to experience tidal forces. On Earth, we observe this tiny change in force as a major change in the height of the seawater. In some cases, like the Bay of Fundy in Canada, the sea level can vary by as much as 16.3 m, tall enough to swamp an entire five-story building.

If small forces like these can create big changes here on Earth, what do you imagine the tidal forces near a black hole might be like?

In our daily lives, we experience one Earth gravity worth of acceleration. It is the force that keeps us stuck to the ground. However, there is a very slight difference in the forces that pull on our feet compared to the forces that pull on our head unless of course you are lying perfectly level.

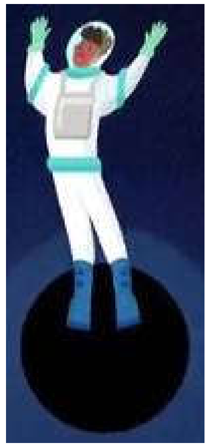
Let us calculate the difference in acceleration by rearranging a version of Newton's formula for universal gravitation.

$$a = \frac{2GMh}{r^3}$$

In this equation *a* is going to be the difference between the acceleration of two points separated by a height *h* above a body of mass *M* and radius r. Let us see what the differences for a person on the surface of the Earth:

$$M_{Earth} = 5.97 * 10^{24}\,kg$$
$$r_{Earth} = 6.3 * 10^{6}\,m$$

For someone my height about 1.8 m, I experience a difference in acceleration of a miniscule 5.5 * $^{10-6}$ m/s^2. Compared to one Earth gravity, that is less than 2 ppm. Definitely not something that we can sense. However, let us do the same thing again, this time taking the mass and radius of the nearby black hole Cygnus X-1. It has a mass of approximately 15 solar masses, or 3 * 10^{31} kg. For simplicity, let us just say it is a Schwarzschild black hole with a radius of 44 km. Plugging in these numbers, gives us a difference in acceleration between my head and my feet of 8,000,000 times the force of gravity.



Of course, we would not survive such incredible differences in forces, and scientists have named this effect spaghettification (i.e. noodle effect), which is not so much delicious as it is horrifying. Essentially, as you approach a stellar-mass black hole, you will eventually be pulled into a thin strand that once called itself a human. Not a pretty way to go, but that was for a small stellar-mass black hole. Let us see how would it affect someone around a super-massive black hole.

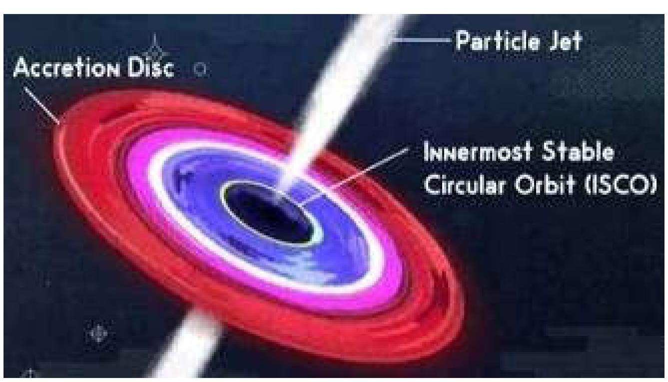
Sagittarius A star is the name of the black hole at the center of our Milky Way galaxy. Weighing in at 4,000,000 solar masses Sagittarius A has a corresponding Schwarzschild radius of 12,000,000 km, which is more than eight times the diameter of our own Sun. Putting these values into our equation, yields a difference in acceleration of a measly one 10,000 times the gravity on Earth.

What is going on here?

As it turns out the larger a black hole, the more gradual the changes in the gravity field as one approach. In the movie 'Interstellar,' the writers chose to use a fictional super-massive black hole called 'Gargantua,' which is why the crew of the 'Endurance' were able to get so close to the event horizon without feeling tidal forces.

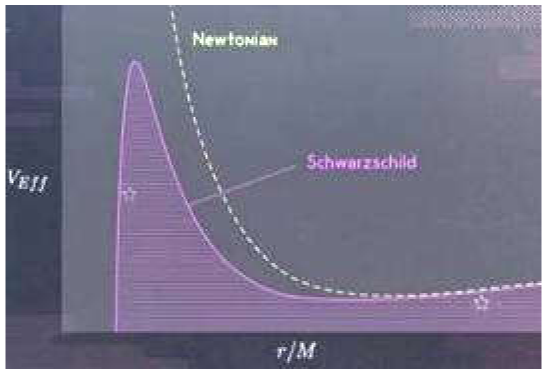
However, massive tidal forces were apparent on Miller's planet when gigantic waves circulated the planet. For super-massive black holes, the tidal forces at the event horizon are much gentler than the forces around a smaller black hole. In fact, if you were a space traveler, you would need to be extremely careful in the area around a super-massive black hole, because it is possible, you could cross the event horizon and not even realize it.

8 Innermost Stable Circular Orbit (ISCO)



After a thorough investigation of the accretion disk around the black hole, we will end this module teetering at the edge of stability. Note, we are not discussing the black holes event horizon just yet, but we can stay indefinitely in a stable orbit around a black hole as long as we do not cross a boundary called the 'Innermost Stable Circular Orbit.' If Cygnus X-1 were not rotating, it would permit stable orbits about three times the distance from its event horizon. We will learn in a later lesson what happens when a black hole rotates, but this would allow stable orbits as close as 130 km from the center of Cygnus X-1, or 90 km from its event horizon.

The innermost stable circular orbit is the boundary that distinguishes between stable orbits, which do not require energy for an object to stay in orbit there, and unstable orbits, which will pull you in towards the black holes event horizon. Unless you have very powerful engines like the 'Enterprise' in 'Star Trek.' The innermost stable circular orbit, which we will henceforth just call the ISCO, defines the inner edge of the accretion disk beyond which material will fall freely, and become captured by the black hole.



Somewhere between the accretion disk and the event horizon, Newtonian gravity stops being a good approximation. The gravitational field becomes much stronger than Newtonian gravity predicts. This increased strength of the gravitational field is due to corrections by Einstein's theory of general relativity. The result is that the gravitational pull becomes much stronger within the region bounded by the ISCO, and stable orbits predicted by Newtonian gravity are no longer stable.

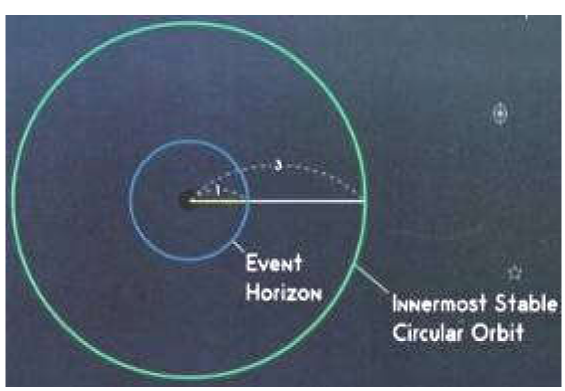
Since the gravitational potential around a black hole is represented by a Schwarzschild potential, there are five kinds of orbits that we can find. There are stable and unstable circular orbits, orbits that we call bound precessing orbits, scattering orbits, and plunging orbits. For a Schwarzschild black hole, the solution to the equations of general relativity tells us the peak of the potential occurs at a radius:

$$r = \frac{6GM}{c^2}$$

Recall that we have already encountered the radius of a Schwarzschild black hole when we were experimenting with the escape velocity formula. The Schwarzschild radius, which describes the event horizon of a black hole, occurs at:

$$r = \frac{2GM}{c^2}$$

Quite the coincidence. The only difference between the innermost stable circular orbit and the event horizon is a multiple of three.



Actually, this makes life quite a bit easier for us since we can simply state the ISCO of a non-rotating black hole is three times further from the black hole's event horizon. The key here is that it is *not rotating*. We have not discussed much about rotating black holes yet, and we will get more into it in a later lesson. Nevertheless, I just cannot help myself here, because the ISCO will actually change when we are considering a rotating black hole. This is apparent in the movie ‘Interstellar’, when the crew of the ‘Endurance’ visit Miller's planet very close to the ‘Gargantua’ event horizon.

At this point, please watch Astro-101_017.mp4

Video 17 : See and relax

They were able to do it safely, because a rotating black hole can actually have an ISCO that is much closer to the event horizon. In an extreme case, a rotating black hole could have an ISCO coincident with the event horizon, but we will see more about that in an upcoming lesson.

One final note about the ISCO. We have only covered matter interacting with the gravitational field of the black hole. If instead we looked at light, we would have found a different result. The ISCO for light orbiting a non-rotating black hole can be a factor of two closer to the event horizon. Photons can be trapped in circular orbits at the light ISCO radius, and orbit many times before escaping. We can then detect these photons, which would look like they are coming from a sphere of light surrounding the black hole, which scientists sometimes call the photon sphere.

9 Teetering On The Edge

On our approach to a black hole using our example of Cygnus X-1, we identified a number of structures that are visible from the environment around the black hole. Now, we find ourselves teetering on the edge of stability on the precipice of the ISCO. Looking away from the black hole, we can see the bright material within the accretion disk being fed by a nearby companion star within its Roche lobe. Looking above the disk around the black hole, a faint glow is evidence of the corona, and stretching brightly off the poles of the black hole, we see towering jets, columns of accelerating plasma that can stretch thousands and millions of light-years in length. Our next step takes us within the ISCO radius. There, without a powerful rocket engine to escape, we will eventually fall across the black hole's event horizon.

Crossing The Event Horizon

1 Introduction

Welcome to the black hole. Now that we have arrived in orbit around a black hole's event horizon, it is time to dip into the interior. The event horizon is a strange, one-way street in the Universe, preventing light and material that have crossed from returning. However, the event horizon is thought to hide something even stranger in the interior of the black hole, the singularity. We will also put a positive spin on things and find out what happens when a black hole rotates. Finally, we will take a look at the black hole's weird cousin, the wormhole, and see if it is possible to travel to distant regions of the Universe.

2 The Event Horizon

Black holes have an inside and an outside separated by a boundary called the event horizon.

What is an event horizon? What does it look like, if it looks like anything at all?

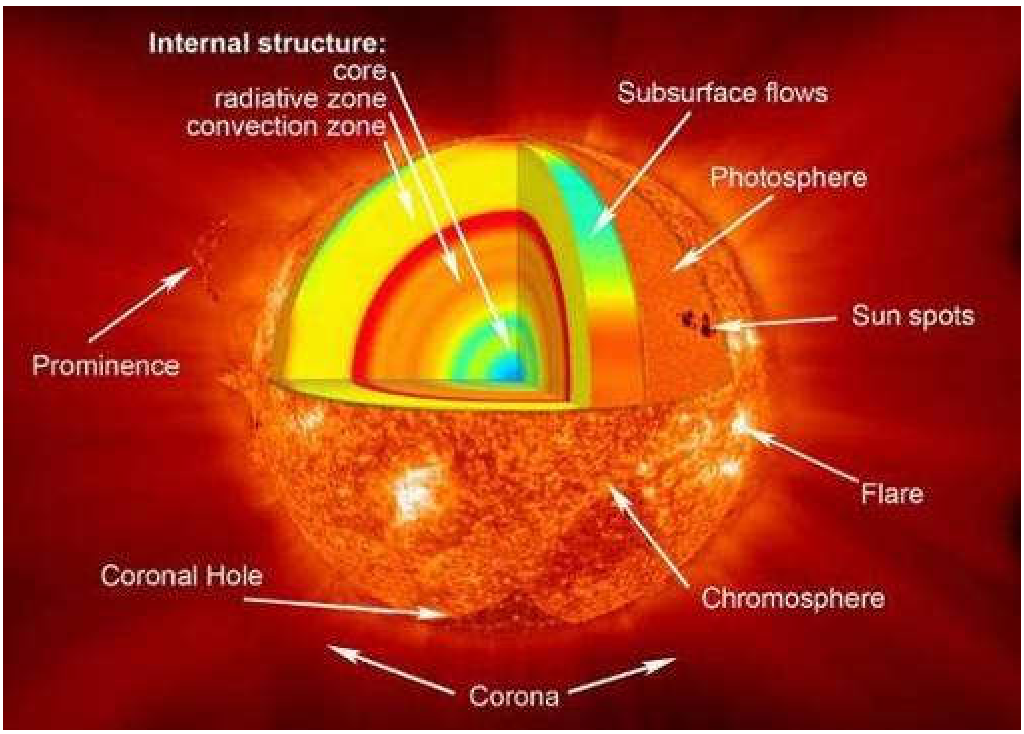


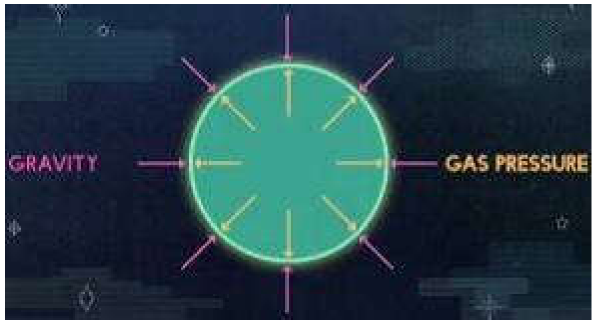
Illustration 94 : Internal structure of the Sun

Let us explore this concept by revisiting what we mean when we talk about the surface of an object like the Sun. We often think of the Sun, or any other star, as a big ball of gas, which has a surface, but it is an oversimplification to say that the entire star's gas lies inside this surface. Some of the Sun's material is continually escaping from the hot and energetic surface. The solar wind pushes a small amount of the Sun's gas all the way to the outer edges of the solar system. This is the material that generates the auroras here on Earth after all.

For stars, we generally define the surface, known as the photosphere, to be the outermost layer of the Sun. The photosphere is what we see when we look at the Sun in visible light. If we try to look deeper inside the Sun, the hot gas blocks the light. Therefore, we cannot actually see deeper than the photosphere. Beyond the photosphere, there are additional regions of the Sun where gas interacts, such as the chromosphere and the corona, but those layers are very faint and difficult to see. As you can imagine, seeing exactly where the Sun's surface is located, is a matter of scientific definition.

Although black holes do not have a surface, scientists have defined a boundary to separate the interior of the black hole from its exterior. A black hole's event horizon is a boundary that separates the black hole's interior, which we are unable to see from the outer region. However, unlike stars, the black hole's event horizon is much easier to define, because it is impossible for gas or light to escape from the event horizon. We say that the event horizon is the surface or boundary of a black hole, not as a rigid body, but as the point of no return for material that has fallen in.

2.1 Hydrostatic Equilibrium



Why is it impossible to have a ball of gas inside of the event horizon?

It all comes down to a concept called hydrostatic equilibrium. In a further lesson, we discovered that hydrostatic equilibrium is the balance between gravity and gas pressure in the interior of stars. Gravitational attraction tries to bring all the gas in the star towards the star center, but gas pressure creates an outward force that prevents further gravitational collapse. When the stars are in balance, the star is stable and can stay the same size for a long time, like our Sun.

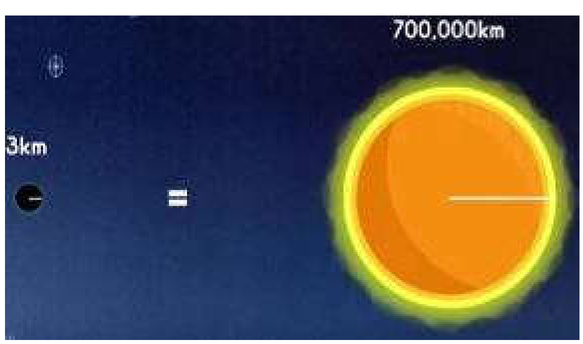
Suppose we take a star and compress it into a smaller volume, overpowering gas pressure at the interior. The matter in the star will be squashed, and feel a stronger gravitational pull towards the center, which requires a larger gas pressure in order to push outwards to balance the star.

Is it possible to continue compressing the star into smaller and smaller regions?

No. If you compress the star's gas within the star's Schwarzschild radius, the gas pressure required to balance gravity becomes infinite. It is not possible to create infinite gas pressure, therefore, gravity wins the battle, and the star's gas will have to continue falling inwards. It is impossible for any matter to be at rest inside of the black hole's event horizon.

The event horizon can be understood by observing how light rays are bent by the gravitational field of a massive object. We know that if there is no gravity, light travels in straight lines, just like a ball rolling on a flat surface travels in a straight line. Just as the sheet is deformed by the presence of the weight, space-time is deformed by massive objects, like a star or a black hole. When we roll a ball on a curved sheet, it does not travel in a straight line; instead, its path is curved towards the central mass. The closer the ball's starting point is to the mass, the more the path of the ball becomes curved.

Light is deflected in the same way by the mass of a star or a black hole. If a star and a black hole have the same mass, the deflection angle is the same for photons travelling on paths that are the same distance from the object, assuming the light path stays outside of the object.

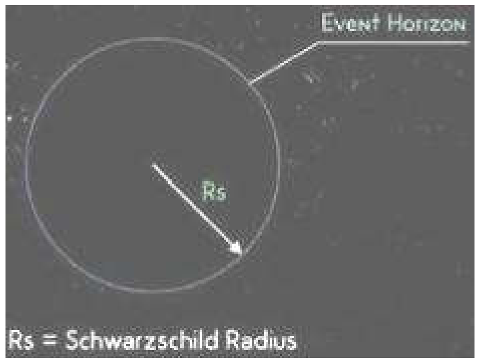


We must remember that a black hole with the same mass as the star is much denser. If you recall that the Sun's radius is 700,000 km, but a black hole with the same mass as the Sun has an event horizon radius that is only 3 km. This means that it is possible to get much closer to the center of a black hole than a star.

2.2 Schwarzschild Radius

The radius of a non-rotating black hole is sometimes called the Schwarzschild radius, named after Karl Schwarzschild, the first person to solve Einstein's equations for strong gravitational fields. Einstein's equations were thought to be so difficult that Albert Einstein himself said that nobody would ever be able to solve them. However, only a year after Einstein published the equations, Karl Schwarzschild found the first solution, which happened to describe a non-rotating black hole.

What a coincidence that Schwarzschild, whose name means black shield in German, was the first to describe the concept of a black hole. In a further lesson, we explored the equation for Schwarzschild radius, which is:



$$R_S = \frac{2GM}{c^2}$$

In this equation, R_S is the distance corresponding to the Schwarzschild radius, M is the black hole's mass, G is Newton's gravitational constant, and c is the speed of light. For black holes that do not rotate, the event horizon is a sphere with a radius that is simply proportional to the black hole's mass. Therefore, if you double the mass of a black hole, the radius of the sphere doubles, too.

If you put numbers in for the Sun, you will find that the Schwarzschild radius is 3 km. Physicists often simplify key equations by folding terms that occur repeatedly. In this case, the equation for the Schwarzschild radius is simplified to:

$$R_S = 3km * \left(\frac{M}{M_{Sun}} \right)$$

Equation 22 : Simplified Schwarzschild Radius

We now have the event horizon radius scaling with a ratio of masses, or in other words, it is dependent on how much more massive a black hole is than the Sun. This is helpful as it makes the numbers a little easier. If we were to visit Cygnus X-1, which has a mass that is 15 times larger than the Sun's mass, the radius of the black hole would be:

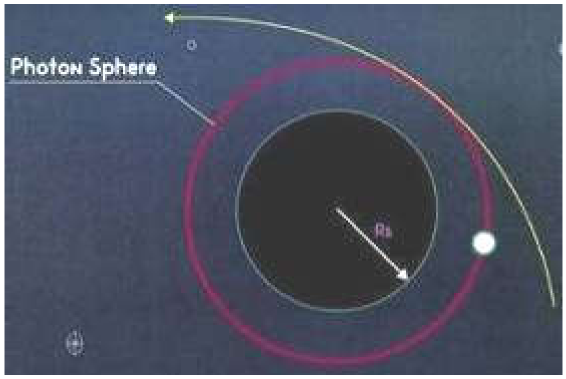
$$\begin{aligned} R_S &= 3km * 15 \\ &= 45km \end{aligned}$$

Still pretty small. The supermassive black hole at the center of the Milky Way has a mass that is 4,000,000 times larger than our Sun. This means that its event horizon is 12,000,000 km. That might sound like a big distance, but the largest black hole in our galaxy is smaller than the distance between our Sun and Mercury. A black hole would need to have a mass that is 50,000,000 times larger than the Sun before the event horizon would be as large as the distance between the Sun and the Earth.

Since the event horizons of supermassive black holes are further away from the black hole center, the tidal forces at the event horizon are smaller for black holes with larger masses. As we learned earlier, tidal forces can be pretty hazardous to an astronaut's health. This means that if you get to choose which black hole to visit, you should choose a larger black hole mass. It is estimated that a black hole should be at least 1,000 solar masses in order to be safe to visit.

Since the radius of a black hole is proportional to its mass, if matter falls into the black hole, the event horizon grows larger. In most cases, this is an incredibly small change. However, if two black holes collide, they can merge into one significantly larger black hole. In case you are wondering, Stephen Hawking proved that it is impossible for a black hole to split into multiple black holes. We will talk more about this in a later lesson.

2.3 Photon Sphere



If we shine a flashlight in the direction of a black hole, the closer the light is aimed towards the black hole, the more curved the light beam will become. As we aim a flashlight closer and closer, we discover that there is a special distance at which light from our flashlight begins traveling in circles around the black hole. This is an area called the photon sphere, which corresponds to a radius that is 1½ times larger than the radius of the event horizon. The photon sphere is similar to the ISCO for particles, except that circular photon orbits are unstable. If a photon becomes trapped within the photon sphere, only a small nudge is enough to kick photons away from the black hole, or to send them spiraling inward.

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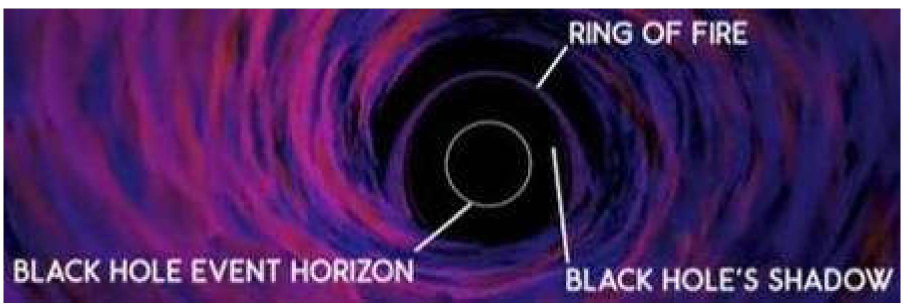
Video 18 : Animation of the 'Ring of Fire'



Current telescope technology is on the verge of capturing images of a photon sphere. New telescopes, like the 'Event Horizon Telescope' and others in development, should be able to capture images or the ring of fire. If we aim our flashlight closer to the black hole than the circular photon orbit, photons emitted from the flashlight will move on plunging orbits that will end up crossing the event horizon. Any light entering the event horizon is unable to escape. If we can image the region outside the event horizon of a black hole, we would see a region with no light emission that is sometimes called the black hole shadow.

What will happen to an astronaut that is far from the black hole?

Let us consider a situation in which both an astronaut and a distant observer are equipped with flashlights capable of emitting one pulse of light per second.

If they shine these pulsing flashlights at one another while the astronaut falls towards the event horizon, what observations would we expect them to see?

We already learned that gravitational time dilation would stretch the time intervals that the faraway observer sees. As the astronaut falls into the event horizon, the time interval between the pulses received by the observer stretch to infinite amounts of time, even though the astronaut may have only spent a few hours falling into the black hole. Since the event horizon is a one-way street in space-time, the astronaut falling towards the black hole will continue receiving signals from a distant observer at exactly the same rate of one pulse per second. The astronaut even continues to receive the signals after crossing the black holes event horizon. Remember, the event horizon is asymmetric, just like one-way street. Light can enter the black hole, but it cannot escape.

The in-falling light pulses from the distant observer do not change as they pass through the event horizon to be observed by the astronaut. Just as there is no wall of gas left over from us compressing a star, there is nothing-special-marking location of the event horizon. This makes a trip to a black hole extremely dangerous. If you manage to survive the tidal forces near a black hole, it is easy to accidentally crossover the event horizon since it seems like an unremarkable location in space when you are traveling through it. Therefore, if you do travel to a black hole, be sure to calculate exactly where the event horizon is before you approach.

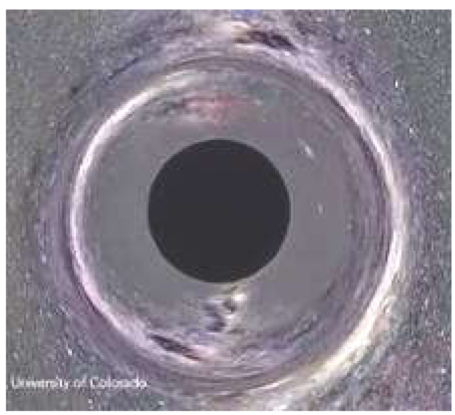
We know that nothing entering a black hole's event horizon can escape. Not even light. This means that you cannot sneak a look at what is inside, and let people outside know what is happening. While you obviously would not risk putting your head into a black hole, if you are sitting inside your rocket orbiting just outside the event horizon, you could lower a camera past the event horizon. However, in order to take a picture of the inside of a black hole, the electrons in the camera would need to travel faster than the speed of light to send any information back up to your spaceship. We expect that the structure holding the camera will be ripped apart, and that the camera would fall inwards before any photos could be taken.

2.4 Singularity

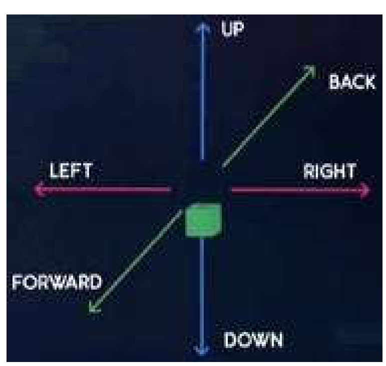
Even though, in theory, we cannot pass information about the interior of a black hole past the event horizon, we can deduce some of the properties of a black hole's interior. One object theorized to exist by Sir Roger Penrose is called the singularity, an object so foreign to the laws of physics that our understanding of them is incomplete. Singularities are thought to be such dreadfully ugly objects that we think the event horizons themselves are there to shield us from seeing it. This yet unproven conjecture is sometimes called 'Cosmic Censorship Hypothesis,' and we will go into more gory detail in the next lesson.

3 The Singularity

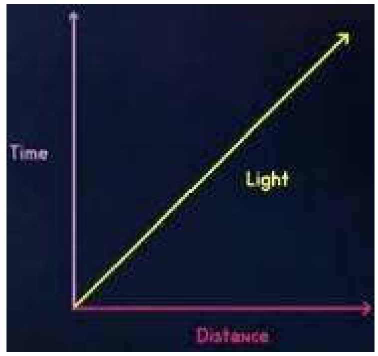
Now, let us do something unwise, and travel past the event horizon of a black hole. Knowing that we would like to get there without being spaghettified, let us choose a supermassive black hole as our destination, therefore, that tidal forces do not rip us apart on our approach.



Once we pass through the event horizon, we will be in the strange world of a black hole's interior. Although it is impossible to send information about the inside of the black hole to the Universe beyond the event horizon, there are no laws of physics that would prevent us, observers within the event horizon from making scientific discoveries. The first thing that we would notice looking away from the black hole is all of the light emitted by the stars and galaxies outside of the black hole. It definitely is not black inside a black hole. If we shine a flashlight, we find that no matter what direction we try to aim the light, the rays always end up pointing inward to smaller values of the black hole's radius.

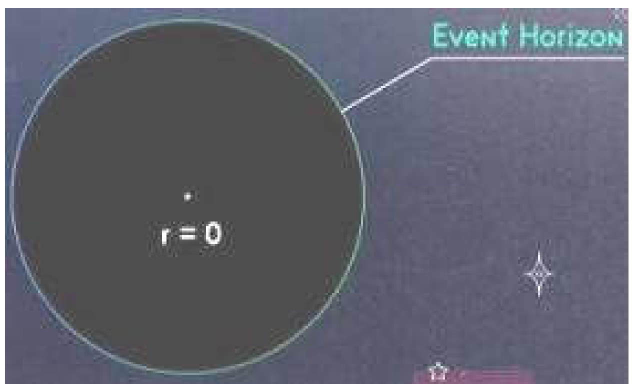


Before we examine the peculiarities inside of the event horizon, it is worth pointing out just how strange our Universe actually is. We have three spatial dimensions that allow us to move about front to back, left, and right, as well as up and down.

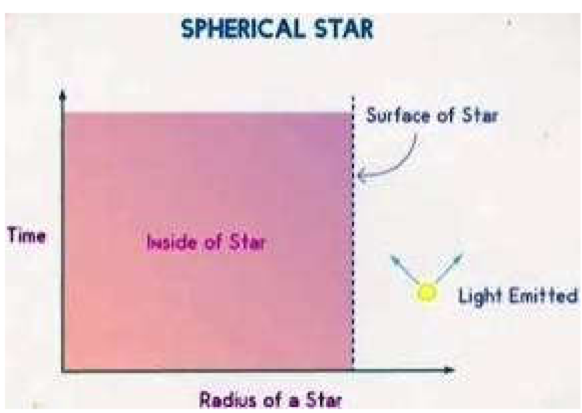


We also consider time, a dimension even though we can only move forward. Something very peculiar happens to the dimensions of space and time at the event horizon of a black hole. Within the event horizon, the radial coordinate, which measures how far you are from the black hole singularity, switches meaning with the dimension of time.

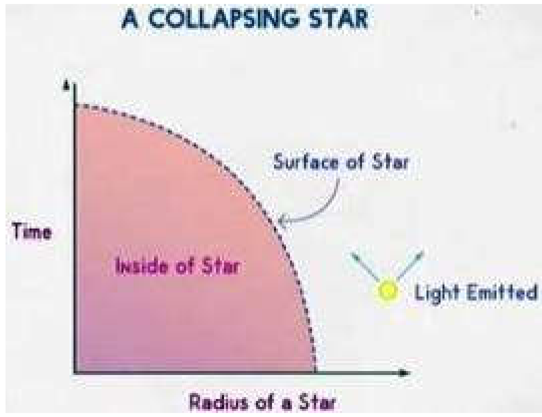
Think about it like this, when we are out in the Universe, we cannot go backwards in time. However, in the interior of a black hole, we can no longer go backwards in space. This may give you a headache, but moving to smaller values of radius is really the same thing as moving towards a time in the future. Escaping the black hole would require that you move to larger values of radius, which is equivalent to going backwards in time. Since you cannot go backwards in time, you have no choice but to continue to future times, which is the same thing as moving towards smaller value of radius towards the center of the black hole.



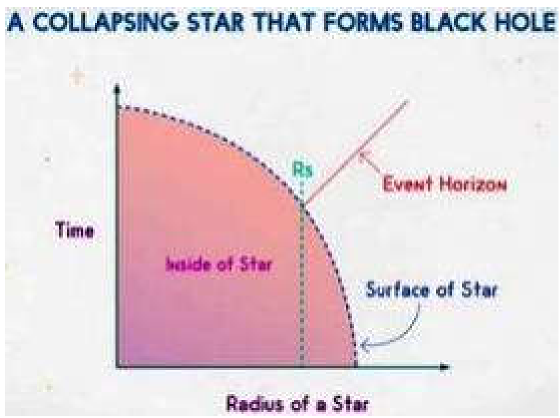
This might not make much sense if you are thinking of the black hole as a sphere surrounding the point $r = 0$. This is a good enough illustration for the region outside of the event horizon, but it is not a good representation of the inside of a black hole.



We can make a better illustration of a black hole by first thinking about how to represent a star that has the same size for all time. In this diagram, since the star is a sphere, all we show is the size of the star's radius. Time runs upwards in this diagram, and to the right we plot distance from the center of the star. Since the star has the same size for all time, the surface of the star is just a straight vertical line. On this diagram, light rays travel on 45° angle lines.

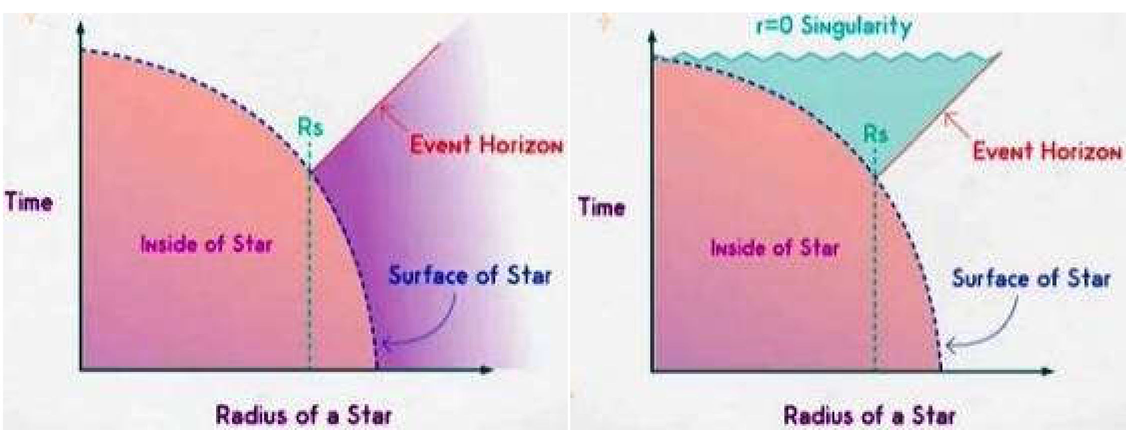


Now let us draw a graph of a star that is a sphere that is collapsing to become smaller in size. We are using the same coordinates on this graph; therefore, the surface of the star is a curve instead of a straight line. As time increases upwards on this graph, the distance between the surface of the star and the center of the star decreases with time.



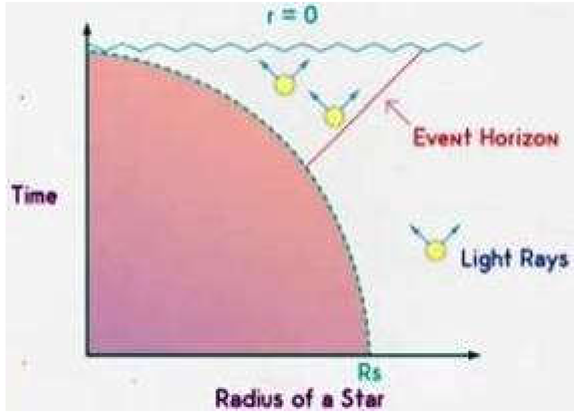
Let us take the collapsing star and allow it to form a black hole. In this illustration, we have the same surface of the star; they get smaller as time increases. However, at one special moment in time, the surface of the star is at the same location as the Schwarzschild radius, R_S. At this moment of time, the event horizon forms and is represented by a straight line drawn at a 45° angle.

3.1 Penrose Diagram



The region below the event horizon is the region outside of the black hole and the region above the event horizon is the inside of the black hole. The jagged line corresponding to what we thought was a point is actually a time in the future.

This is a simplified version of a Penrose diagram, which is a tool scientists use to understand the interiors of black holes. More advanced versions of Penrose diagrams further compact the dimensions of space to a finite region. Since the radial coordinate r takes on the characteristic of a time coordinate, smaller values of distance from the center correspond to later times. There is no way to avoid the flow of time, therefore, any object that is dropped into the event horizon ends up falling to the center at r = 0.



In this diagram, light rays travel on upward paths at 45°. Light emitted in the region outside of the event horizon can go in two directions, to the right, which means escaping from the black hole; or to the left, which means falling into the event horizon. Light that is emitted inside of the event horizon still travels on upward directed 45° angled lines. Light that is sent in left or right hits either the jagged r = 0 line.

Having a powerful rocket engine would not help you to escape. All this can do is slow down the inevitable since your rocket cannot travel faster than light. The amount of your own personal proper time that it takes to fall from the event horizon to the center of the black hole depends on the mass of the black hole. A higher-mass black hole is larger in size, and the fall takes more time. The time it takes to reach the center is characterized by this tidy equation:

$$T_{Fall} = 15 * 10^{-6} s \left(\frac{M}{M_{Sun}} \right)$$

Therefore, for the black hole Cygnus X-1, with a mass that is 15 times larger than our Sun's, the equation dictates that you would have about 0.2 ms to relish in the experience of touring the black hole's interior. This amount of time is about how quickly your eyelids take to blink, therefore, you will not even be able to think about snapping a photo of the scene.

We now have another great reason to visit high-mass black holes. We can have more time to enjoy the sights. For example, if we were to choose a supermassive black hole that is 1,000,000,000,000 times the mass of the Sun, we would have around 4 h of proper time to fall from the event horizon to the singularity at the center. The center of the black hole at zero radiuses is the location of the singularity. Since this location corresponds to a time in the future, you would not see or experience it until the precise moment of time when you reach it.

How would objects behave when they arrive at the singularity?

Well, since observers are not able to report back what happens here, we examine what theoretical models of the interior tell us. No matter how massive the black hole is, the equations suggest that all of the mass that has fallen into the black hole accumulates at the center, and is squashed into zero volume. They also predict that an observer would feel infinitely strong gravitational and tidal forces from which no known object would survive destruction.

At this point, you might be a bit confused about the terminology, therefore, let us unpack the word singularity a bit more. To start, I will state that physics and mathematics have an unequal relationship. In order for physicists to make predictions about physical processes, we need mathematical equations in order to describe likely outcomes. However, it is possible to write down all mathematical expressions that do not seem to have any connection to physics at all. Many times in the history of science, mathematicians have come up with equations that do not seem to have anything to do with physics. At only many years later, do some physicists discover that the equations actually describe some physical phenomenon.

Mathematical equations that describe physical processes are limited to certain circumstances. Outside of those limits, the equations begin to fail, giving non-physical answers. For an example, consider Newton's equation for the attractive gravitational force between two objects with mass 1 and 2 separated by a distance *r*.

$$F = \frac{GM_1M_2}{r^2}$$

What happens if we allow the distance *r* between the two objects to come infinitely close together, allowing the masses to occupy the same spot in space?

In that case, we would set r in the equation to zero, which would mean that we would be dividing by zero in this equation. Dividing by zero is undefined in mathematics and is normally something that you should avoid doing. In order to make sense of this situation, we provide some physical context. What we should remember is that mass takes up space. Therefore, it is physically impossible for the centers of two masses to have zero separation.

Since Newton's equation of gravity fails when $r = 0$, we should treat them only as a good description of nature if the distance between the objects is > 0. The result when $r = 0$ is called a singularity. What this tells us is that at $r = 0$, our equations just do not make any sense. This type of situation is one that prompts us as scientists to look for a new explanation and, more specifically, a new equation.

We already learned that Newton's equation of gravity is an approximation to those of Einstein.

Does that mean Einstein's description of gravity could help us remove the annoying singularity at the center of black holes?

Unfortunately, the answer is no. In fact, Einstein's equations predict a divergence of the gravitational fields. Meaning, the problem of the singularity gets even more troublesome than we would have otherwise predicted using Newton's equation.

One shortcoming of Einstein's equations for gravity is that they do not include our modern knowledge of quantum mechanics. Quantum mechanics distinguishes itself by introducing the concept of wave functions to describe the positions of particles. Quantum mechanics governs the behavior of particles at scales where Einstein's equations fail. Einstein's equations for gravity assumed that we know the locations and speeds of particles exactly. However, the Heisenberg uncertainty principle, a foundational concept of quantum mechanics, tells us that there is a limit to how precisely we can determine the location and speed of particles.

3.1 Quantum Gravity

In order for physicists to understand the behavior of the singularity, we need to combine quantum theory with general relativity, which remains a mystery at present. If we knew how to create such a theory, we would call it quantum gravity.

One proposed method is called string theory, and is a promising set of equations that might describe quantum gravity. However, scientists have not yet managed to solve these equations, or make any useful predictions with them. You, dear listeners, can take this up as a challenge, the prize for successfully driving a theory of quantum gravity could win you a Nobel Prize.

Many physicists think that as you fall in towards the black hole singularity, the standard equations of Einstein's gravity describe what happens to you for most of the trip, until the distance, or really, time, between you and the singularity becomes much smaller than the size of an atomic nucleus. The region of space-time that is close to the singularity requires quantum gravity for accurate predictions. Since we do not understand quantum gravity, we can only speculate. Perhaps, quantum gravity removes the concept of a singularity, and could describe the potentially existence of a nice remnant.

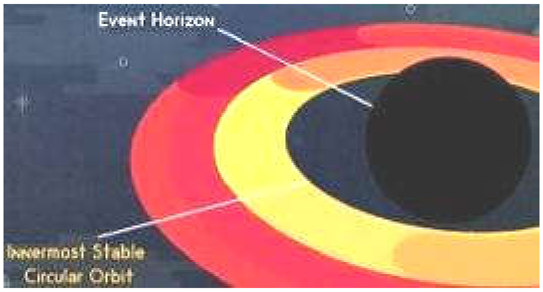
We really have no way of knowing, since the singularity occurs at a time in the future, and it cannot affect us as we fall in. Ultimately, our lack of understanding of quantum gravity does not affect our journey to the center of the black hole until the moment when we are about to reach the singularity.

As we have alluded to before, the singularity inside of a Schwarzschild black hole is a bit of an annoying mathematical object. The singularity simultaneously exists everywhere at the interior of a black hole, but only at a specific moment of time. Given that singularities in our Universe are not visible to us, as far as we can tell they are all hidden behind event horizons, scientists have conjectured the existence of a principle to hide singularities from view, called the 'Cosmic Censorship Hypothesis.'

Einstein's gravitational equations predict many different types of singularities. We will encounter a new type of black hole singularity shortly, a ring singularity. These other singularities are more like a wall that has a fixed location in space and last for a long time. Suppose you run towards the wall, you can see it in front of you as you approach it and if you do not stop, you will smash into it. A singularity that is like a wall is called a naked singularity. A naked singularity is problematic since we do not have any way to protect what it might emit.

The 'Cosmic Censorship Conjecture' states that in realistic astrophysical situations, naked singularities cannot form. In other words, the laws of physics keep singularities cloaked by event horizons. Possibly, only singularities like the Schwarzschild version can exist. The 'Cosmic Censorship Conjecture' is yet unproven, but at present we do not see any evidence for naked singularities existing in nature. Well, with one exception, the 'Big Bang' itself is quite possibly a naked singularity. It is likely that in nature, all singularities are surrounded by event horizons. Which is why I am excited about direct observational evidence for the event horizon of a black hole.

4 Spinning Black Holes



There have only been a few occasions where we have discussed the properties of a rotating black hole. Back in a further lesson, we discovered that the rotation of a black hole changes the location of the ISCO. For a non-rotating black hole, the ISCO was three times farther from the center of the black hole than its Schwarzschild event horizon, but for a rotating black hole, the ISCO can shrink until it exactly matches up with the black holes event horizon. It should be noted that as a black hole spins faster and faster, it also pulls the event horizon inwards. Both the ISCO and the event horizon can be as small as ½ of a Schwarzschild radius for a maximally rotating black hole. In fact, now would be a good time for us to fess up about a little white lie we have been telling you.

4.1 Frame Dragging

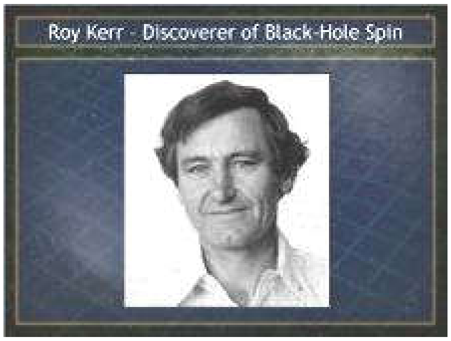
Any realistic black hole will have angular momentum and will therefore be spinning. We know that black holes must be spinning, because in-falling particles carry angular momentum, and we have an annoying law of conservation of angular momentum, which tells us that particles will contribute angular momentum to the black hole. While it is convenient for scientists to learn about the properties of black holes from non-rotating solutions, the reality is that the 'perfect' Schwarzschild black hole is unlikely to exist.

We should also note something very strange about black hole rotation. There is a limit to how quickly they can spin. We will talk a little bit more about the mathematics behind this concept shortly, but the basic idea is that the rotation of a black hole drags space-time along with it. Similar to the way that water spirals down a drain, space-time rotates around a rotating black hole. This is a process called frame dragging.

4.2 Kerr Equation Of Angular Momentum

The rotation of a black hole depends on its original spin and the cumulative effects brought about by all of the material that has fallen into it. A problem arises when we begin to talk about angular momentum. Previously, we had taken an object's mass and multiplied it by the distance from the point of rotation to calculate its moment of inertia.

Do you see the problem here? If all the mass of a black hole is trapped within a zero volume singularity at its center, how is it possible for a black hole to have a moment of inertia?



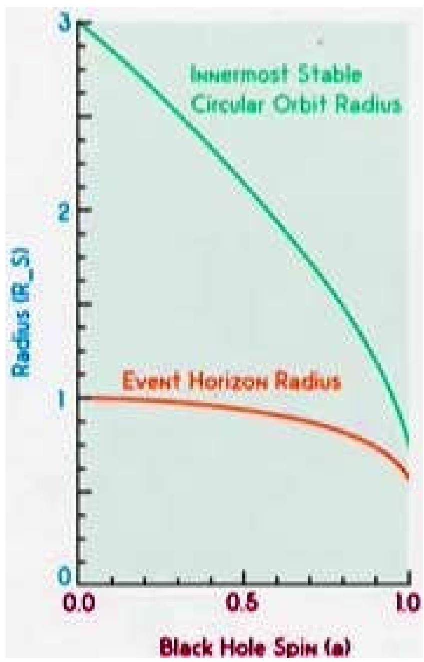
Well, in 1963, a scientist named Roy Kerr developed a solution to Einstein's field equations, which precisely described the properties of a rotating black hole. In the original research, Kerr described how he characterized the angular momentum of a black hole, but mentions how the moment of inertia cannot be characterized except to say that they are very small. The rotation of black holes is usually characterized by a number between zero and one called *a*, which is calculated by the equation:

$$a = \frac{Jc}{M^2 G}$$

Equation 23 : Kerr equation

J is the angular momentum of the black hole, *M* is its mass, and *G* is Newton's gravitational constant. If you have not figured it out already, *c* is always used to describe the speed of light.

If a black hole is not rotating at all, unlikely I know, *a* takes on the value of zero. If a black hole is spinning maximally, meaning it has reached the upper limit we mentioned before, a takes on a value of one. As the black hole spins faster, the event horizon and the ISCO are pulled inwards. The rotating black holes event horizon shrinks to about half the size of a non-rotating Schwarzschild black hole with the same mass, and the ISCO decreases from three times the Schwarzschild radius to coincide with the event horizon at half the Schwarzschild radius from maximum rotation.



With that said, I now feel comfortable showing you how the radius of the ISCO changes from three times the Schwarzschild radius down to 1½ as rotation of the black hole changes from *a* = 0 to *a* = 1.

In case you are wondering, the maximum allowed spin frequency at the event horizon of a solar mass black hole is 16,000 Hz. The event horizon of a black hole with the same mass as the Sun can spin as fast as 16,000 $^1/_s$. For other masses, we can simply calculate:

$$\text{Maximum frequency} = 16{,}000 Hz * \frac{M_{Sun}}{M}$$

Therefore, higher mass black holes must spin at a slower rate. For a black hole about 36 times the mass of the Sun, you would find the maximum rotation corresponds with about 440 Hz, or for you music aficionados, the same as a concert 'a' note.

The underlying mathematics of Kerr solution would take an entire course to discuss, but its impact within the scientific community is characterized best by Nobel Prize winning physicist, Chandrasekhar, who said:

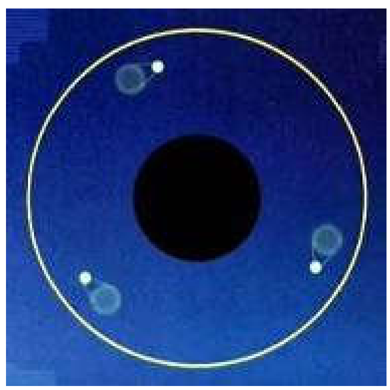
'In my entire scientific life extending over 45 years, the most shattering experience has been the realization that an exact solution of Einstein's equations of general relativity discovered by New Zealand mathematician Roy Kerr provide an absolute exact representation of the untold number of massive black holes that populate the Universe.'

4.3 Non-Rotating Black Hole

As a rotating black hole, twist the space-time around it like the ripples in a whirlpool, the twisting and warping of space-time itself begins influencing the particles and objects within it. Far from the black hole, these forces gently swirl objects around the black hole. The closer you approach the event horizon of a rotating black hole, the more extreme this interaction becomes eventually pulling anything falling past the event horizon into complete lockstep with the black hole.

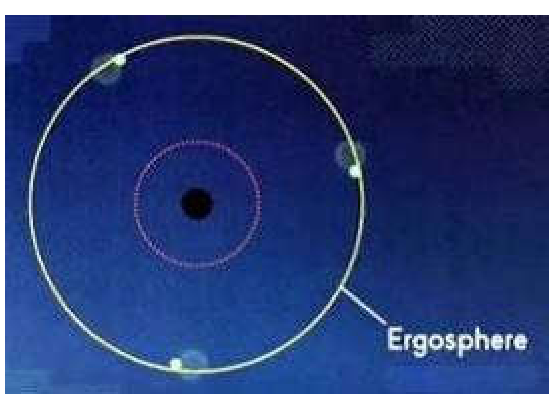
Let us have a top-down look at a non-rotating Schwarzschild black hole. In this diagram, there is a central non-rotating black hole, and each point here represents some source of light. When a light source is far from the black hole, the light propagates outwards in all directions. As the sources approach the event horizon, the light sphere begins to distort towards the black hole center. When one of these light sources crosses the event horizon, the light becomes trapped inside.

4.4 Rotating Black Hole

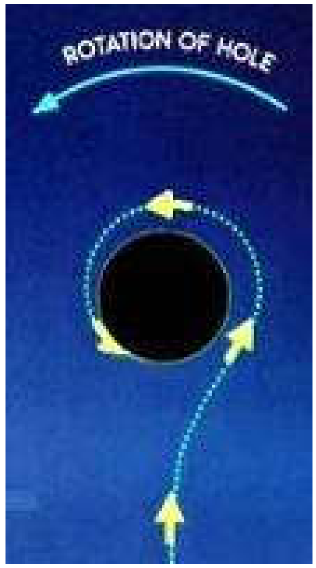


Now, let us impart some spin on this black hole changing it from a Schwarzschild black hole into a rotating Kerr black hole. Since the Kerr black hole just drags space-time, light sources far from the black hole begin to see a shift in the direction their light spheres propagate. However, there is an even more interesting change when a black hole is rotating. Not only does the event horizon shrink from the non-rotating Schwarzschild radius down to about ½of its normal size for maximum rotation, but also particles falling directly inward begin spiraling around the black hole even though there are no forces acting on them.

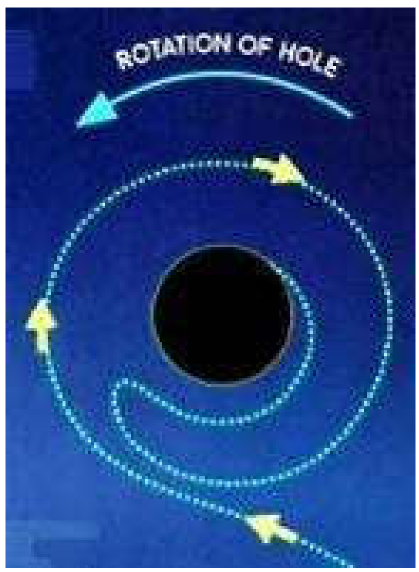
4.5 Ergosphere



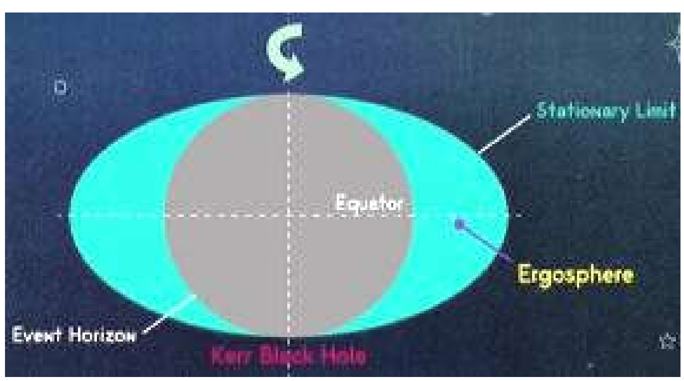
There is a special distance from a rotating black hole that defines a region called the ergosphere. The outer boundary of the ergosphere is called the stationary limit, and outside of the stationary limit, a spacecraft can park with respect to the black hole.



However, within the stationary limit, no spacecraft can ever appear at rest to a distant observer.



Even spacecraft entering the ergosphere orbiting the opposite direction to the rotation of the black hole will eventually be pulled by the spiraling space-time into a co-rotating trajectory.

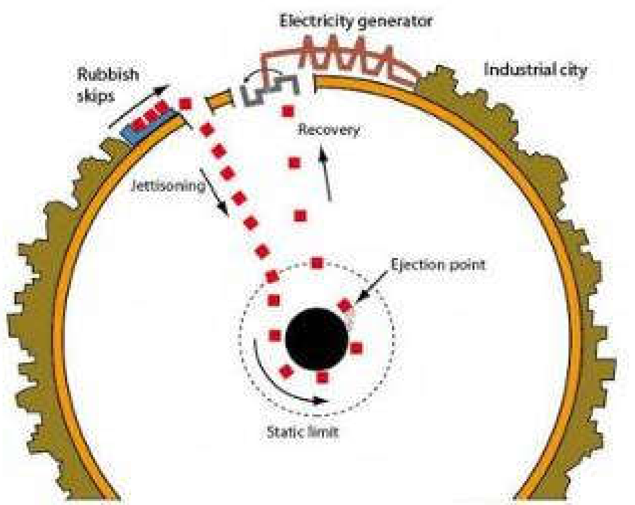


Although the word sphere is part of ergosphere, the ergosphere is not actually spherical, but rather an ellipsoid. While the event horizon is still spherical, the ergosphere envelops the event horizon only touching at the spin axis of the event horizon. It is good to remind ourselves that the ergosphere and the event horizon are boundaries and not objects, therefore, they do not interact with each other in the same way that particles interact with them.

4.6 Penrose Process

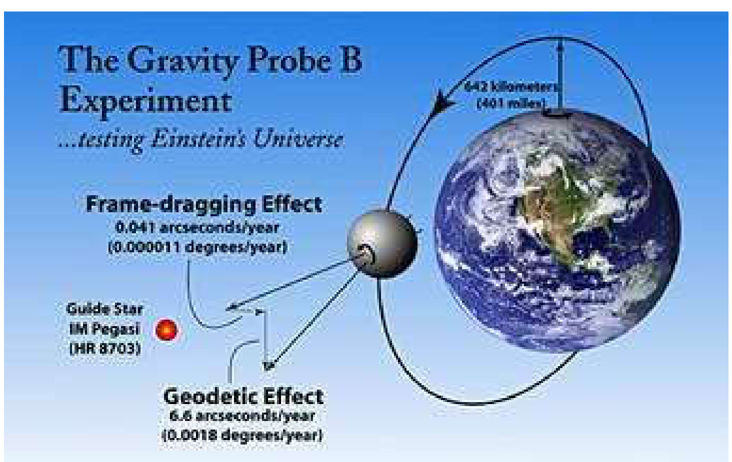
I will emphasize now that a clever spaceship captain can still escape from the ergosphere, and can in fact steal rotational energy from the black hole. The word ergosphere comes from the Greek root 'ergon,' which means work. The ergosphere is so-named, because it is theoretically possible to extract the energy from the black hole's rotation with some clever tricks. For example, from within the ergosphere, you could throw a ship's garbage against the rotation of the black hole, accelerating the ship forward, and in the spiraled space-time, end up with more kinetic energy than you started out with. In a case like this, you are stealing energy from a black hole's rotation. Roger Penrose first described this process of stealing energy from a rotating black hole in 1971, which is why we call it the Penrose process. Without going into detail, within the ergosphere it is possible for the energy of a particle to become negative, a consequence of the change in coordinate system at the stationary limit.

4.7 Dyson Sphere



Ultimately, what this means is a super-advanced civilization could survive around a rotating black hole, extracting a surplus of energy using the Penrose process until a black hole's rotational energy has been sapped. They could also do the reverse, storing energy as the angular momentum of a black hole and extracting it at a later time.

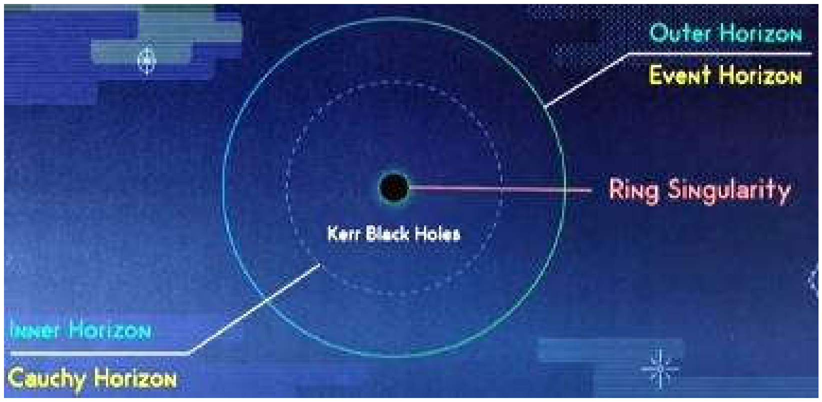
4.8 Gravity Probe B



It might seem far-fetched to you to be talking about spiraling space-time and frame dragging, but it is possible to measure the gravitational effects of a rotating body without a black hole at all. In fact, a space probe aptly called 'Gravity Probe B' was launched back in 2004 to investigate just how strong the frame dragging effects are here on Earth. Gravity Probe B carried four incredibly precise gyroscopes in order to measure these effects. At the time of their construction, these gyroscopes were the most spherical objects ever made, differing from perfectly round by no more than 40 atoms on a sphere roughly the size of a ping-pong ball. Since the effects are quite a bit weaker around a planet like Earth compared to black holes, it took four years of operation before NASA reported agreement with Einstein's theory of general relativity.

4.9 Cauchy Horizon

We have been hiding a few details of the Kerr black hole behind the veil as it were. The event horizon of a Kerr black hole should really be called its outer horizon, because the mathematics tell us that there must be another inner horizon hidden inside. The outer horizon is basically the same as the event horizon; it is the boundary from which nothing can escape. Even if you have fallen through the outer horizon, it is still possible to receive information from beyond the event horizon right up until you fall through the inner horizon, often called the Cauchy horizon.



The Cauchy horizon marks the boundary within a black hole, where information from the entire history of the Universe is compressed. An observer approaching the Cauchy horizon would see more and more of the history of the Universe, essentially being battered by the extreme energies that are compressed within that region. Crossing the Cauchy horizon would be perishing enough simply due to the incredible energy densities, one would need to survive.

However, there is yet another mathematical danger lurking within the Cauchy horizon, the Kerr black hole's ring singularity. Unlike the point-like singularities we have been discussing for Schwarzschild black holes, the singularity of a rotating Kerr black hole is a ring instead of a point. The Cauchy horizon may be the Universe's last stand at preventing observers from violating cosmic censorship and glimpsing the singularity.

4.10 Naked Singularity

What happens if the black holes spin increases?

The distance between the outer and inner horizons become smaller, and the two horizons will coincide if the black hole has maximal rotation. If the black hole spins faster than maximal rotation, the equations predict that the horizons will disappear, and the singularity will become visible to the whole Universe. Since there will be no event horizon, the resulting thing will not be a black hole, instead we call it a naked singularity. Cosmic censorship predicts that it is impossible to spin a black hole faster than the maximal amount.

One final note about rotating black holes. If it were possible to pass through the Cauchy horizon, and if it were possible to survive the cosmic censorship, it might be possible that an extremely talented astronaut could pilot their ship past the ring singularity, and emerge into another Universe. What that Universe might look like or what you would find there is still unknown. While it may be tempting to plunge into a Kerr black hole hoping to survive the journey to a new Universe, there may be a less dangerous possibility, which we will talk about next; wormholes.

5 Wormholes

I grew up in the orchards of the Okanagan Valley in Canada, and apples have been an important part of my life. Apples also played an important role in the work of Newton, as he reputedly described the moment he began to wonder about gravity as being the result of seeing an apple fall out of a tree. Often, an apple is used as an analogy to describe another important concept in gravitational physics. I am talking about a specific solution to Einstein's field equations, the Schwarzschild wormhole.

Of course, the name wormhole comes from the idea that worms are caterpillars who feast on the flesh of an apple can tunnel through the interior in order to create a shorter path between two points on the surface. In this analogy, the skin of the apple is our regular 4D space-time, and the flesh of the apple is of some higher dimension in a hyperspace. Carl Sagan famously said about wormholes:

'It's just possible that you might emerge in another part of space-time, some where else in space, and some when else in time.'

5.1 Einstein-Rosen Bridge

What exactly is a wormhole?

The short answer is that a wormhole looks like a black hole, but instead of a trash compacting singularity at the center, a wormhole opens back up into a distant region of space-time. In 1916, Ludwig Flamm was studying the Schwarzschild black hole solution to Einstein's field equations, when he discovered that a second solution was possible. This second solution described a white hole, a region in space that ejects matter from its event horizon. Flamm then lined up and joined the necks of both the black hole and the white hole and boom; the concept of a space-time bridge was born. Today, we call this an Einstein-Rosen bridge after it was rediscovered by Einstein and Rosen in 1935. It was not until 1957 that the word wormhole was first used to describe a connection between two points in space-time, this time by scientist Charles Misner and John Wheeler.

Let us be very clear right off the bat here, white holes, and wormholes are purely hypothetical and, unlike black holes, there is no observational evidence of their existence. Mathematically speaking, wormholes can exist and not only can they tunnel through space, but it is also possible for them to tunnel through time. Throughout the 60^s, 70^s, and 80^s, wormholes entered popular culture through novels like 'A Wrinkle in Time', 'The Forever War', and Carl Sagan's 'Contact.' Even modern video games like 'Portal' and 'Portal 2' employ wormholes as their central game mechanic. In fact, the mathematical development of wormhole theories seems to be heavily influenced by science fiction.

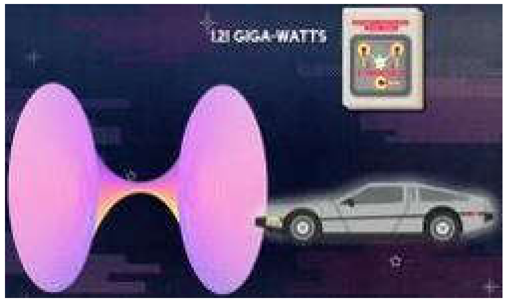
When Carl Sagan was writing his science fiction novel 'Contact,' he approached the famous black hole physicist Kip Thorne, and asked him how it will be possible for a human being to travel vast distances across the galaxy using a rotating black hole. Thorne suggested instead that Carl consider travelling through wormholes. When Thorne put pen to paper to start figuring out the mathematics, they discovered that wormholes are inherently unstable. Not only would the neck of a Schwarzschild wormhole be too narrow to permit the passage of human being, but the wormhole itself would close up extremely quickly making it possible to only squeeze through a bit of information before the wormhole is destroyed. However, Thorne realized the neck of the wormhole could be held open with some kind of material that would repel the wormhole's walls gravitationally. In reality, we have no idea what kind of material this would be, all of the regular material in our Universe acts through gravitational attraction.

If regular matter will not do the job, Thorne posited that a spherical wormhole could be kept open using a form of material with a negative energy density. In fact, when the 'University of Alberta's' physicist Don Page was approached by Thorne, Page demonstrated that any shape of wormhole requires a negative energy density to be held open in much more elegant mathematics.

5.2 Exotic Material

Physicists call this exotic material, and although there are no examples that we know of, there is nothing written in the laws of physics that prevent it from existing in our Universe. The distinguishing feature between an unstable and a traversable wormhole is, therefore, the presence of this exotic material.

One such traversable wormhole was theorized by a scientist named Homer Ellis, who demonstrated a solution to the Einstein field equations that permit safe passage through the wormhole in either direction. Named after him, the Ellis wormhole was used as a template for the wormhole in 'Interstellar,' which carries the crew of the 'Endurance' from an orbit around Saturn to 'Gargantua' in a distant region of the Universe.



We do not touch much on the science of time travel, but one of my favorite movies on the subject has to be back to the future. In it, 'Doc Brown' accidentally sends 'Marty McFly' travelling backwards in time from 1985 to 1955 in his time travelling DeLorean. One of my favorite fan theories for how the DeLorean works is, that the 'flux capacitor' stores enough energy, 1.21 GW, and not jiga as 'Doc Brown' says, to create the negative energy density required to amplify a tiny wormhole. Just big enough and just long enough for the DeLorean and its passengers to squeeze through the wormhole before it closes behind them.

Inside A Black Hole

1 Black Holes: The Final Frontier

You unlock this door with the key of the singularity. Beyond the event horizon is a combination of dimensions. Dimensions of space, of time, of imagination. You are falling into a reality of both order and chaos, of theories and information. You have just crossed over into the quantum zone.

1.1 Quantum Zone

Just like the 1960s cult classic, 'The Twilight Zone,' the interior of a black hole is governed by mysterious forces and strange effects, which sometimes behave in unexpected ways.

Why are bigger black holes cooler than small ones? How can tiny black holes evaporate out of existence?

The answers will require us to leave the comfortable world of gravitation, and examine the effects caused by the random laws of quantum mechanics. Until now, we have assumed that anything falling beyond the event horizon of a black hole meets an untimely demise on the journey to the singularity, but one principle in quantum mechanics tells us a conflicting story. That information can never be destroyed.

What is left of all the starlight, the radio transmissions, the books, and teapots that happened to fall into a black hole? Can we know what has fallen into a black hole?

The answers to these mysteries are central to the search for a theory of quantum gravity. Now, it is time to explore the intersection of quantum physics with black holes.

2 Introduction To Quantum Mechanics

2.1 Electromagnetic Waves

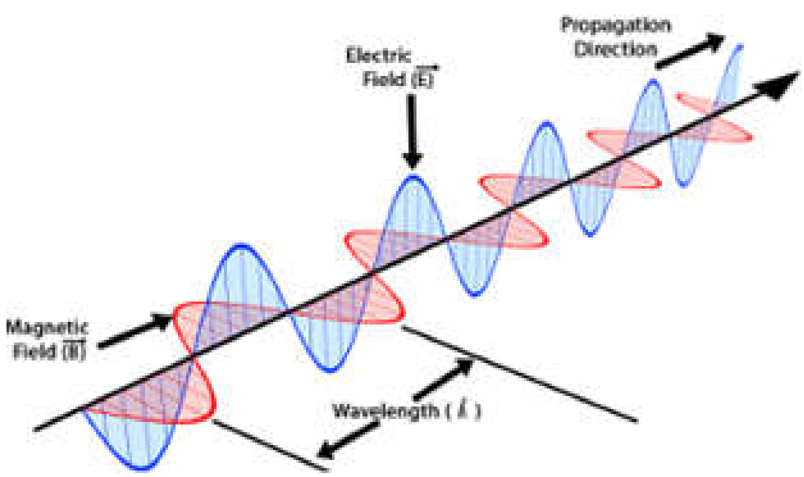


Illustration 95 : Electromagnetic wave

The story of quantum mechanics really begins at the end of the 1800s, a time when scientists thought that the properties of light were completely understood. Their understanding, one that is still fully relevant today, was that visible light is a manifestation of electromagnetic waves. Light has been shown in experiments to be a wave corresponding to the changing electric and magnetic fields. Maxwell had introduced his equations describing the behavior of light waves.

2.2 Blackbody Radiation

There was one problem that remained in that wave description of light, and it really troubled physicists. The standard description of light waves did not correctly describe the light emitted from hot objects, an emission known as blackbody radiation. We know that if we turn on a stove, the element will become hot and glow red, but when we consider light using the physical laws laid out in the 1800s, we would instead predict that our stove would emit more blue light than red and even more UV-light than blue.

The theory of light created in the 1800s predicted the wrong spectrum of colors from blackbody emitters. Theory predicted that the frequency of light increases as the light becomes more and more intense, contributing more and more energy to the spectrum. This is clearly wrong as it results in the stove emitting an infinite amount of energy. When you turn on your stove, it does become hot, and the energy emitted in turn heats your food. However, the energy emitted from your stove is not infinite. Otherwise, turning it on would destroy the planet.

2.3 Quantum

The problem of supposedly infinite energy being emitted from blackbodies came to be known as the 'Ultraviolet Catastrophe.' The ultraviolet catastrophe was a huge problem for theoreticians of the era, and its resolution became the turning point in the history of physics.

Illustration 96 : Max Planck

In 1899, Max Planck was commissioned to study the efficiency of incandescent light bulbs, which shine due to the heat. That same year, he proposed a theory that resolved the problem of the infinite energy emitted by black bodies by introducing a new idea. Electromagnetic waves can transport only a special amount of energy called a quantum, instead of any arbitrary amount of energy. This was the key to explaining why the energy emitted by a light bulb, or any other hot object, is not infinite.

2.4 Photon

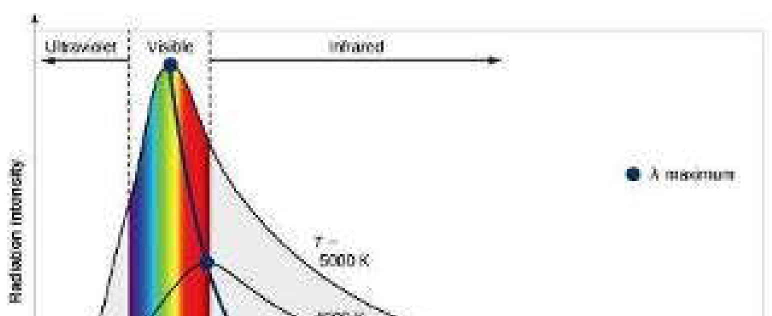


Illustration 97 : Blackbody radiation

The new equations Planck developed with a mathematical foundation to resolving the ultraviolet catastrophe, they correctly describe the color and energy emission properties of a blackbody. This new concept of a quantized packet of light energy was called the photon. To accompany this concept, Planck also introduced a new physical constant, which is now named after him called Planck's constant.

$$h = 6.6 * 10^{-34}\ Js$$

Equation 24 : Planck's constant

The letter *h* is often used for Planck's constant. The -34 tells you that Planck's constant is a very small number. It is hard to wrap your head around how small this number actually is, or what it means, but we will investigate its implications in more detail soon.

Planck's introduction of the tiny constant *h* was mainly a trick to make the math's work properly for blackbody radiation. He did not suggest that it had any true physical meaning. However, Albert Einstein realized that Planck's constant does imply a new physical reality, that light can be thought of as a particle. In a brilliant paper published in 1905, Einstein showed that particles of light, or photons, come in units that are called quanta, where a specific amount of energy is related to each color of light.

If we have light of a certain color, we know its wavelength and its frequency. Einstein introduced a simple equation for the energy of a photon of that color. The energy of a photon is:

$$E = h * \nu$$

Equation 25 : Energy of a photon

This radical idea led to Einstein receiving the Nobel Prize for his work in physics in 1922.

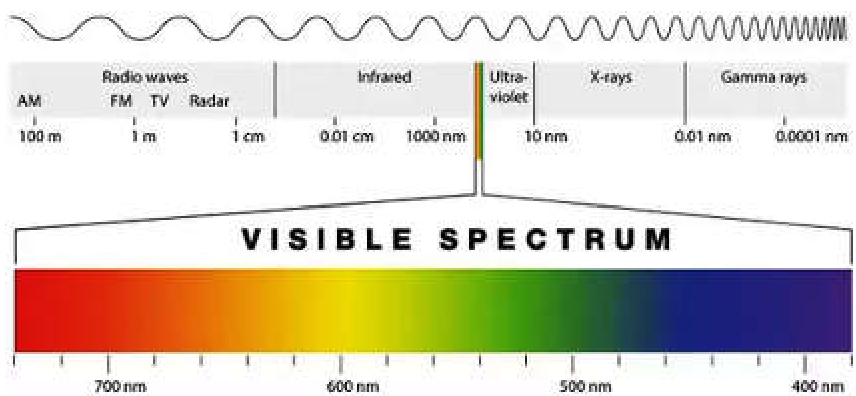
Why was the concept of a photon such a radical idea?

It is radical, because it claims that there is a smallest indivisible amount of energy for light of any particular color.

Think about our modern understanding of matter, we know that matter is made up of fundamental particles that are indivisible. For instance, an electron is a particle that has a specific amount of electrical charge and a specific amount of mass. It is possible to have zero electrons, or one, or two, or any whole number of electrons. However, you cannot have ½ an electron. Matter comes in clumps.

The concept of a photon is similar when you see light of some color; the light is arriving in a group of photons. There might be one, two, or five million photons, but never half a photon. Light also comes in clumps. Light is clumps of energy, while matter is clumps of mass.

Since the value of *h* is so tiny, the amount of energy carried by most photons of light is also tiny. Normally, when we see light, the number of photons is enormous, and therefore, we do not notice the clumpy nature of light. For instance, if you are a couple of meters away from a standard incandescent light bulb, about 10^{12} photons of yellow light enter your eye every second.



The particle nature of light is more obvious when you do experiments with very short wavelength radiation like X-rays or γ-rays. When radiation has a long wavelength, such as radio waves, the wave nature of light is more apparent since the individual photons in the radio spectrum have a wavelength much larger than the length of a human. The quantized nature of light is a fundamental principle of modern physics. Lasers, for instance, can only be understood if we acknowledge the existence of photons.

2.5 Wave-Particle Duality

The interesting thing about light is that it can be described using the properties of both, waves, and particles. Our being able to describe light in these two ways is called 'Wave-Particle Duality' of light. In fact, we are not just able to describe photons, but all fundamental particles as both particles and waves. Wave-particle duality is one of the foundational ideas of quantum mechanics.

2.6 DeBroglie Hypothesis

Einstein came up with the radical idea that photons can have both wave and particle properties.

What about matter? How can matter ever behave like a wave?

In 1923, a graduate student named Louis DeBroglie asked this question and hypothesized that a particle such as an electron could have some wave-like features. One of the most fundamental features of a wave is that it has a distance over which properties repeat. The distance is what we call the wavelength, and we use the Greek letter λ to represent wavelength. DeBroglie's hypothesis was this. If a particle has a known mass and velocity, then it will also have a wavelength.

$$\lambda = \frac{h}{m * v}$$

Equation 26 : DeBroglie wavelength

We call this the DeBroglie wavelength. Since the mass and velocity are in the denominator of the equation, the wavelength becomes large if either the particles mass, or velocity, are small. Therefore, since an electron has a smaller mass than a proton, if they both are travelling at the same speed the electron will have a larger wavelength. By the way, setting the speed to zero in this equation makes no sense, since anything that has a temperature above absolute zero (0 K) has some motion. We do not ever actually have particles with zero speed.

2.7 Diffraction

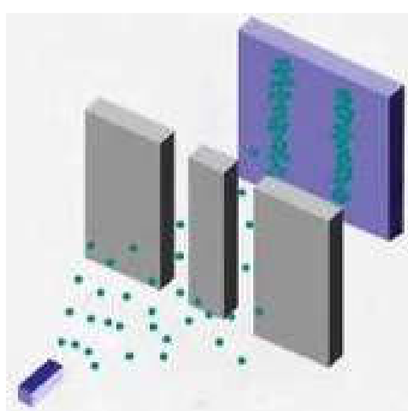
One of the important properties of waves is that it does not make sense to talk about where a wave is located. Say, I asked you to point to the location of a water wave traveling across an ocean.

Could you point to a specific location that defines where the wave is?

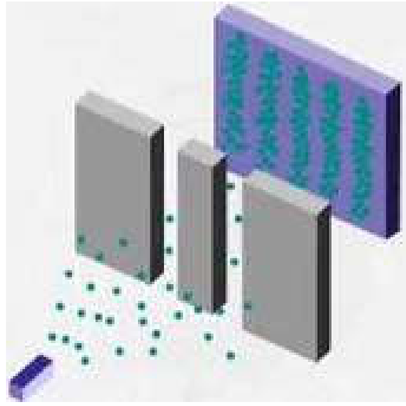
It can be difficult to define. When a wave is forced to travel through a small region like this hole in the wall it spreads out. The resulting circular wavelengths can be seen in a photo of ocean waves passing through the hole in a rock wall. We call the effect of spreading wave's diffraction.

However, can matter really act like a wave?

When you are considering distances that are smaller than the wavelength for a clump of matter, as is often the case in quantum mechanics, some strange patterns begin to emerge.

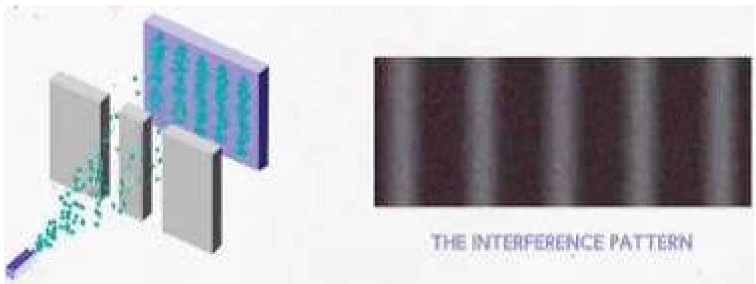


In this illustration, we see a stream of particles travelling towards a wall with two holes. The DeBroglie wavelength of the particle is tiny compared to the distance between the slits. Since the wavelength is very tiny, the particles move in a way you would expect particles to move. They land in two stripes on the far wall.



Now we have the same experimental setup, but we choose particles with a large DeBroglie wavelength compared to the slit separation. We could do this by either choosing slower speeds or smaller mass particles. When the particles pass, through the slits, they spread out in the same way that water or light waves would spread out and they interfere with each other.

2.8 Interference Patterns



The resulting pattern when they hit the wall has a series of stripes called an interference pattern. The interference pattern is not obvious at first, but over time as more particles arrive and interfere with each other a series of bright and dark stripes are seen.

An example of this would be in the use of an electron microscope. An electron microscope is similar to an optical microscope, but instead of photons to see the detail in an image, an electron microscope shines a beam of electrons. Actually, since the electrons matter wavelength is so small compared to the wavelengths of the photons, an electron microscope has more powerful magnification than regular light-based microscopes.

2.9 Uncertainty Principle

The fact that matter can also be described using the properties of waves tells us that it would not make sense for us to know the exact location of a matter particle. Instead, we say that a particle is likely inside an envelope bounded by its DeBroglie wavelength, but the DeBroglie wavelength depends on how fast the particle is moving. If the particle is moving fast then its wavelength is small, if the speed is slow then its wavelength is large.

This idea led Werner Heisenberg to introduce a concept called the Uncertainty Principle. It is difficult to say exactly where a wave is or what exactly its momentum is. In fact, there is a limit to exactly how well we can figure out these quantities. In other words, the position and momentum of any wave has uncertainty. Heisenberg bridged this idea of uncertainty to particles using his formula for matter waves, which resulted in the creation of the 'Heisenberg Uncertainty Principle.'

$$\delta_x * \delta_p \geq \frac{h}{4\pi}$$
$$\delta_x = \text{error in position}$$
$$\delta_p = \text{error in momentum}$$

Equation 27 : Heisenberg uncertainty principle I

Here is an example. Let us say we are studying a beam of protons, and we want to know where they are and how fast they are going. The uncertainty principle sets a limit on how well we can know each quantity. This is a strange aspect of quantum mechanics. The more you know about a particles position in space, the less you know about its momentum through space.

For instance, if we could pin down a protons location to a small interval called λx, we could only determine the protons momentum to within a small interval according to the Heisenberg uncertainty principle.

$$\delta_x * \delta_p \geq \frac{\hbar}{2}$$

Equation 28 : Heisenberg uncertainty principle II

In this equation, we use the symbol ħ, this is not a typing error, and this is the symbol that represents the reduced Planck's constant.

$$\hbar = \frac{h}{2\pi}$$

Equation 29 : Definition of ħ

Since some physicists think that writing ħ is easier than dividing by two π.

The important thing that the uncertainty principle tells us is that we cannot know exactly where a particle is located and what its speed is. If you are very certain about where a particle is located then you cannot accurately know the particles speed and vice versa.

There is also an energy-time version of the uncertainty principle. The equivalent energy-time version of Heisenberg's uncertainty principle is:

$$\delta_E * \delta_t \geq \frac{\hbar}{2}$$

Equation 30 : Energy-time version of the uncertainty principle

We will explore what this means for black holes in the following lesson.

3 Hawking Radiation

So far, quantum mechanics seems pretty weird. Niels Bohr, responsible for planetary model of the H-atom, once said, ‘Anyone who is not shocked by quantum theory has not understood it.’ That may be the case, another famous physicist, Richard Feynman, once said, ‘I think I can safely say that nobody understands quantum mechanics.’ Now, Feynman did not mean that quantum mechanics is a useless theory, but that the quantum world behaved so strangely, compared to our macroscopic world, that our human intuitions cannot be relied upon to predict what will happen.

3.1 Quantum Tunneling

Quantum tunneling is just one such example of how strange quantum mechanics can be.

How can tiny particles vanish on one side of a wall only to appear on the other side?

If we recall from our last lesson, we do not know exactly where particles are as a result to the uncertainty principle.

If we do not know exactly where something is, how could a wall know either?

That is the basic principle behind quantum tunneling. That indeterminacy, or uncertainty, can lead to a whole host of outcomes, but quantum tunneling is related to a process within black holes called Hawking radiation, therefore, we need to understand that in order to continue.

As we saw previously, one of the fundamental relations of quantum mechanics is the Heisenberg uncertainty principle. In a practical sense, it states that no matter how accurate our instrumentation, the experiments we conduct will always be limited in the accuracy of their results by at least $\hbar / 2$. However, it is not just our instruments; the entire Universe obeys this uncertainty principle.

The uncertainty principle has an important implication when we think about the vacuum. Normally, you would think of the vacuum as a void space that is completely devoid of material, matter, and energy of any kind. In the context of quantum mechanics, that simply cannot be true, because if there is absolutely nothing, that would imply certainty; certainty about the fact that there is no energy or mass in the vacuum. If you are certain that there is no energy in the vacuum, then you are saying that the uncertainty in the energy $\delta E = 0$.

However, the energy-time version of the Heisenberg uncertainty principle states that:

$$\delta_E * \delta_t \geq \frac{\hbar}{2}$$

In essence, you can never be very certain that you have a true vacuum, since δ_E has to be > 0. The uncertainty principle tells us that what we think is a vacuum actually has, for brief moments of time δ_t, particles appearing and disappearing. This quantum view of the vacuum is sometimes called the quantum foam.

3.2 Quantum Foam

In general, the uncertainty principle is meaningless in everyday life. We never measure things so precisely that we run into such a limit.

However, what if instead we zoom down into the quantum world, what do you suspect we would see?

Illustration 98 : Quantum foam (Artist's view)

Let us shrink down in spatial dimensions to about the size of an atom, and in the time dimension therefore, that we are living through nano seconds as if they were seconds. Already you can see that space-time itself is strange at the quantum scale. Scientists call this mass the quantum foam. This is an artist's illustration of the quantum foam. As you can see, the foam appears to be frothing with activity.

What is going on down here?

Since we have shrunk ourselves down in space and in time, we are living in the cold reality of what the uncertainty principle enforces on the Universe, for lack of a better term, uncertainty. Down here, the foam can essentially be anything; a proton-antiproton pair here, an electron-muon-neutrino entanglement there. The quantum foam might even generate tiny wormholes. As long as these species last for only a short time, they can have lots of energy.

3.3 Virtual Particles

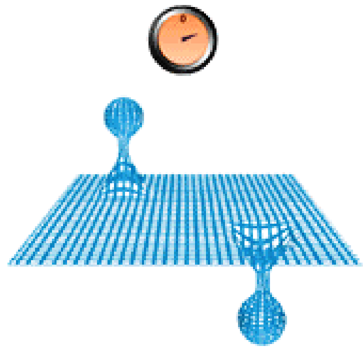


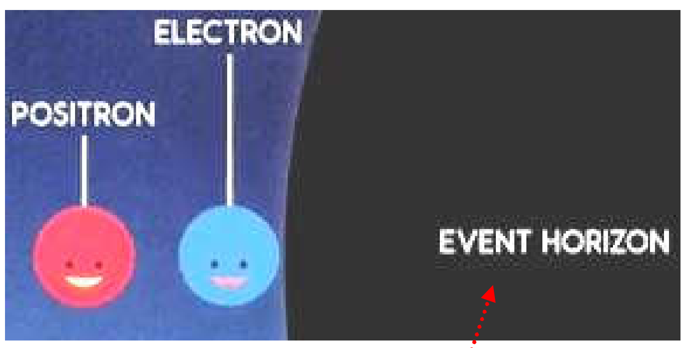
Illustration 99 : Virtual particles

Physicists call particles born in the quantum foam virtual particles, because essentially, they exist for such a short period of time those we in the classical world barely measure their existence. We can borrow energy from the Universe as long as we pay it back very quickly.

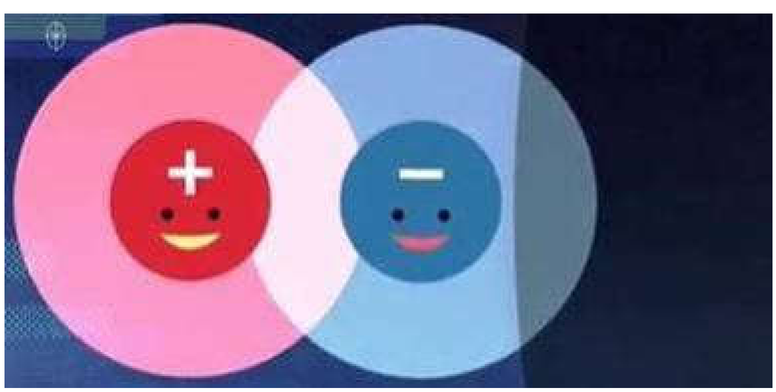
A question we might ask is, what happens if we put a black hole nearby, and zoom in on the quantum world at the boundary of the event horizon? Are virtual particles pulled across the event horizon?

Classically, we would say no. For one, the quantum foam is not a result of classical theories like general relativity, but given its existence anyway, we generally thing that virtual particles do not last long enough to fall in. However, we also have to consider where a particle is, because in this Universe we obey the laws of quantum mechanics.

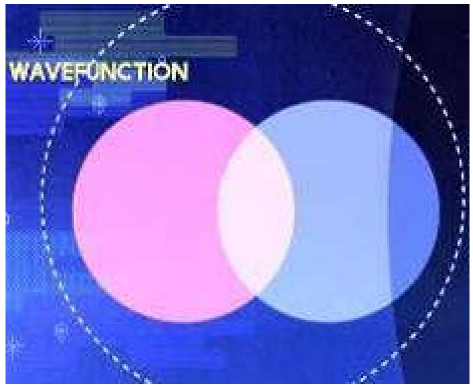
3.3.1 Positronium



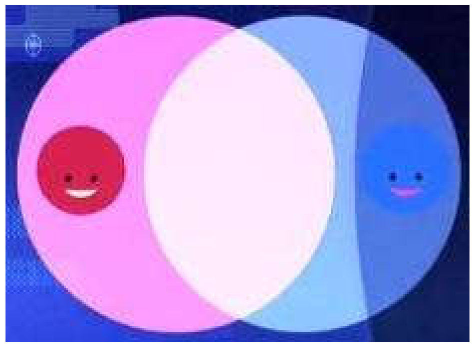
Here we are among virtual particles in the quantum foam, and this black region is the event horizon of our black hole. Let us see if we can pin down an electron and its antiparticle, the positron, when they emerge from the quantum foam. This particle pair is called positronium, because it exists, albeit temporarily, as a quasi-atom, until the Universe decides its time is up, and it vanishes back into the quantum foam.



However, the diagram here does not show a complete illustration, because the electron and positron in the image have definite positions. If we truly draw this properly, each would have a much larger probability density, which is to say, regions within which the particles are likely to exist.



Probability densities characterized by something called the wave function are places where there are probably particles. For example positronium. There is a 100 % chance that we would find them inside this boundary. However, look the way we have drawn this.



There is a good chance that we could find the blue particle not just on the boundary of the event horizon, but within it entirely. That is a bit goofy, you might think.

The particle-antiparticle pair has come into to existence, and before they can repay their energy to the Universe, one of them vanished into the black hole. Now we are in a pickle. We needed that blue particle to annihilate the red one, but instead, now we just have a red one left with no companion, and it does not want to stick around.

Essentially, what you have just witnessed is Hawking radiation, the process by which particles can kind of escape from a black hole. When a particle-antiparticle pair pops out of the quantum foam, right on the boundary of a black hole, the outgoing particle actually steals energy from the black hole system. It does not have to pay the Universe back for that energy, instead the black hole had to pay for that part of the equation.

Not only does that mean that particles appear to come from the event horizon, but also that quantum mechanics allows black holes to evaporate slowly. Therefore, it is pretty obvious that quantum mechanics can do some pretty strange stuff. They can whittle away at a massive black hole until nothing remains.

In the next lessons, we will develop a further understanding of this concept by examining a black hole's temperature, its entropy, and eventually, we will determine how long a black hole has to live in the face of quantum mechanics.

4 Information In A Black Hole

Why are we so concerned about quantum mechanics, as it relates to black holes?

4.1 No-Hair Theorem

The existence of Hawking radiation presents an interesting problem to black hole physicists. Classical black holes can be characterized by three numbers: their mass, angular momentum, and charge. This is a concept called the no-hair theorem, which is a way of saying that information, which is what we mean by hair in this instance, cannot escape from a black hole. However, quantum mechanics tells a completely different story, which has led to one of the biggest unsolved problems of our time, the black hole information paradox.

4.2 Black Hole Information Paradox

In addition to quantum mechanics enabling processes like Hawking radiation, it also throws a bit of a wrench into theories that try to combine quantum mechanics with general relativity. In particular, quantum mechanics requires information to be preserved. Therefore, in order for astrophysicists to have a complete description of a black hole, they will have to find a way to explain the so-called black hole information paradox.

Information can be defined as something, which is an answer to a question. When physicists talk about information, they are generally asking questions about the characteristics and state of something. When we ask about the mass of a star, or we measure what its spectral output is, we are generating information.

Now imagine that you are the commander of a scientific research vessel that is in orbit around a black hole, collecting measurements about the properties of the black hole. You can very easily deduce the mass of the black hole by observing, measuring, and timing how long it takes to orbit the black hole at a given distance. You can also measure the spin of the black hole by comparing the size of the ISCO to the size of the event horizon.

By dropping a couple of test charges and observing their behavior, you can tell the charge of the black hole. Scientists think that most black holes have zero charge anyway. Therefore, as the commander, you have collected all this data, but, oh no, you have accidentally crossed the event horizon. Luckily, you and your crew have survived, but the future is bleak. Given the fuel that you have in your reserve, you can only postpone your collision with the singularity by a few hours, maybe a few days at most.

Is there any way that you could send what you learned back to a distant observer, or does the event horizon prevent information from escaping?

Classical physics, that is to say general relativity, has very bad news for you. There is no way for you to transmit your data across the event horizon. However, being a good spaceship captain, you are brushed up on your quantum mechanics, and you know about two important principles, quantum determinism and the principle of reversibility.

4.2.1 Reversibility

Let us start by unpacking the easy one, reversibility. Reversibility is the idea that physical laws can be used to predict the future or the past of a particular system. If we look at a comet shooting by, not only can we predict where it will be decades from now, but also where it was decades in the past. In some sense, reversibility also tells us that we can go backwards from one state just as well as we can go forwards. In reality, we know that reversibility is more complex than that. Shattered mugs do not suddenly unshatter themselves, but we will address that when we discuss entropy.

4.2.2 Quantum Determinism

On the other hand, quantum determinism is a much stranger idea. Determinism, on its own, is the idea that we can predict the outcome of any interaction if we have sufficient information. If I throw a ball, and you know its direction and how fast it is, where it lands is predetermined.

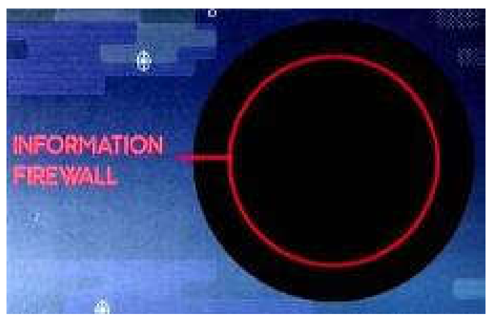
However, quantum mechanics basically deconstructs the notion of classical determinism because of a concept called the Heisenberg uncertainty principle. Since we have limits on what we can measure, we also have limits on what we can predict. Quantum determinism is then telling us a slightly different version of the story. We can predict with certainty what the probabilities of outcomes will be in quantum mechanics.

Since the principles of quantum determinism and reversibility are fundamental to quantum mechanics, we have run into a problem. These two principles together mean that information must always be preserved. However, the no-hair theorem for black holes says that information falling into a black hole disappears when it crosses the event horizon. Many scientists postulate that the information is destroyed somewhere at the interior of the black hole. In the next lesson, we will delve further into this investigation, examining specific theories, which attempt to explain the black hole information paradox.

Which is it? Is information preserved by quantum mechanics, or is it destroyed by general relativity?

There are many possibilities. The information could be destroyed, it could leak out of the black hole gradually, or maybe information could escape in a powerful explosion. Perhaps the black hole itself saves the information like a giant hard drive. The sad truth is that we just do not know. Although there are no known laws that unify gravitation with quantum mechanics, many researchers, including Stephen Hawking, now believe that information is preserved somehow and deeply linked to the process of Hawking radiation. Some researchers have had other interesting ideas.

4.3 Information Firewall



One such interesting idea is the concept of a new boundary within the event horizon, the information firewall. In 2012, a group of physicists, Almheiri, Marolf, Polchinski, and Sully, shortened to AMPS, introduced the concept of a boundary of high-energy quanta that destroy all incoming information, the AMPS-firewall. The AMPS-firewall cleans up some of the inconsistencies of quantum mechanics by providing a mechanism to destroy or scramble the incoming information. However, some scientists think that the firewall creates more problems than it solves.

Present day research, done by Don Page at the University of Alberta, suggests that the information firewall described by the AMPS-group could produce a naked singularity. If indeed there is a firewall within a black hole, Page and his collaborators demonstrate that the firewall could migrate to a region outside of the event horizon, allowing the singularity to become visible to distant observers. We already know how much physicists abhor a naked singularity.

One of Page's research collaborators, Misao Sasaki, has said; ‘If a firewall exists, not only would an infalling object be destroyed by it, but the destruction could be visible even from the outside.’ This is a very complex idea, but it brings up an interesting motivation for physicists. If the firewall idea is right, it means that there is new physics for us to consider. If the firewall idea is wrong, it means that we have uncovered some potential flaws in older physical theories.

Although there is no consensus about how the black hole information paradox will be resolved, there are several leading theories about the fate of information that has fallen into a black hole. One such theory, put forth by Stephen Hawking when he originally described Hawking radiation in 1976, predicts that the outflow particles from the black hole would have unpredictable properties.

Therefore, then what does Hawking radiation actually look like?

5 Black Hole Thermodynamics

Since we seem to have found ourselves in the business of throwing stuff into a black hole, and waiting to see what pops out.

A natural question might be to ask, how does the black hole change when something falls in or comes back out?

Of course, we do our best to respect the no-hair theorem, but we can ask more about black holes than just what happens to their mass spin and charge. After all, if all you have been given are those three values for any particular black hole, I cannot tell you anything about its history compared to a black hole with the exact same three characteristics. Somehow, part of the black holes history is hidden from observation, but astrophysicists have yet another trick up their sleeves.

5.1 Entropy

Entropy is a property that all matter has and is usually explained as a measurement of disorder within a system. That is a pretty good explanation, but it is quite a bit easier to explain it by example: your bedroom. Think about the current state of your bedroom, and on a scale of one to ten think about how messy you would rate it. One being perfectly clean and ten representing the aftermath of a bull in a China-shop scenario.

How many different ways can your bedroom be dirty?

Your socks, specifically, instead of being bundled up in a drawer, might be strewn on the floor. There are many places that you could find messy stocks, on your bed, on the windowsill, under your desk. In fact, there are a huge number of ways that your bedroom can be messy, but there is only one way that it could be perfectly clean. Therefore, by measuring how messy something is, we have learned something about how much entropy it contains.

Entropy is one of the main reasons why we do not experience reversibility in the Universe. Just like your bedroom, there is only one way that a mug is unshattered, but an uncountable number of ways that it can be smashed. What this means is that we rarely see mugs spontaneously going from shattered to unshattered or dirty rooms spontaneously becoming clean, because there are many ways for those systems to evolve, most of them messier than before. For this reason, entropy is not considered to be time reversible.

5.2 Thermodynamics

The behavior of all matter as it relates to entropy, temperature, and energy is codified in a field of physics called thermodynamics. The word thermodynamics comes from the Greek words therm, meaning heat, and dynamics, which means power. Thermodynamics is therefore the study of converting heat into power. Historically, it was motivated through the 1800s by the invention of steam engines and later combustion engines. However, thermodynamics has become an essential tool for astrophysicists, since stars are basically the equivalent of nuclear engines.

5.2.1 Laws Of Thermodynamics

There are four basic laws in thermodynamics, and you will find them surprisingly simple.

The zeroth law is a statement that the temperature of two things is the same when they are in thermal equilibrium. This is a great law, because if it were not true we could never trust thermometers.

The first law is a statement that energy is conserved in isolated systems. This is the principle that thermoses operate on. They attempt to keep your food hot, or cold, by isolating the interior of the thermos from the outside world. Isolation means that ideally no energy is lost to the outside environment. Therefore, for a thermos your food stays hot.

The second law is a statement that heat flows from hotter objects to colder objects, and not the other way around. This might make some intuitive sense. When we warm ourselves by a campfire, we do not think about cold flowing out of our bodies, we think about hot flowing in.

The third law is a statement that as we cool things down to absolute zero all processes stop. This is an extension of our experience, since humans cannot survive for long below about -40° C. However, using a fridge is exactly the third law in practice. Cold food last longer, because decay processes slow down at low temperatures.

The second law of thermodynamics seems pretty obvious. Heat flows from hot things to cold things, and this usually progresses until both objects are the same temperature.

However, how would you go about measuring how far along this equalization is?

The answer is entropy. Just like the example with your messy bedroom, entropy measures how messy a system is. As it turns out this is directly related to an object's temperature. The formulaic definition of entropy is this:

$$S = k * \log(W),$$

Equation 31 : Entropy of a system

where S is the entropy of the system, K is Boltzmann constant and W is the number of equiprobable states the system can be in. Ludwig Boltzmann was so proud of this equation that it was engraved on his gravestone. It is easiest to think back to your messy bedroom for this one. There is only one equiprobable state for a clean room; therefore, the entropy is low. There are millions of ways that your room can be dirty; therefore, the entropy of a messy room is high.

5.3 Entropy Of A Black Hole

Here is the formula to calculate the entropy of a black hole based on the area of its event horizon.

$$S_{BH} = \frac{kA}{4l_p^2}$$

Equation 32 : Entropy of a black hole (Based on area of its event horizon)

Here s is the total entropy, K is the Boltzmann constant, A is the area of the event horizon, and l_p is the Planck length.

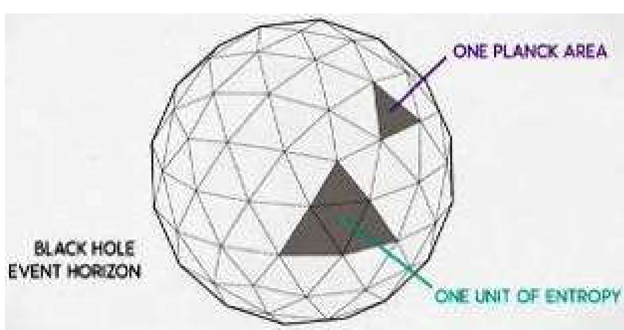
5.3.1 Planck Length

The Planck length is defined by:

$$l_p = \sqrt{\frac{\hbar G}{c^3}}$$
$$= 1.6 * 10^{-35} m$$

Equation 33 : Planck length

The Planck length is incredibly small which is commonly thought of as the smallest distance that can be described by relativity without quantum mechanics.



In some sense, the equation for black holes entropy says that each little bit of entropy that falls into a black hole is encoded as a small patch on the event horizon, one Planck length across.

Before we try to apply entropy to a black hole, take a moment to think.

Does a black hole represent a clean state of all the matter that has fallen in? Alternatively, is it messy?

Black holes are strange objects within the study of thermodynamics, a fact recognized by scientist Jacob Bekenstein. In the early 1970s, Bekenstein asked himself a question very similar to the one I just asked you. At the beginning of the 1970s, it was still believed that nothing could escape from a black hole. Therefore, questions like, 'How hot is a black hole?' made absolutely no sense, since nothing comes out of a black hole, the temperature should be zero. Bekenstein recognize that if black holes did not have well-defined temperatures, maybe they had well-defined entropies. He went on to prove that a black hole's entropy is proportional to the area of the black hole's event horizon.

However, since entropy was well-characterized, should temperature not follow?

We cannot just stick a thermometer into a black hole in order to see if it is running a fever. Instead, we have to consider what is emitted from the black hole as Hawking radiation, causes it to evaporate slowly. Indeed, this was the motivating question that led Stephen Hawking to derive the framework for Hawking radiation. Since quantum mechanics permits black holes to evaporate, they then certainly do not have zero temperature. Hawking's student at the time, Don Page, took the concept of Hawking radiation further, deriving what temperature we could expect a black hole to radiate.

What do you think? Are black holes hot or are they cold?

If you said cold, you are mostly right. The temperatures of black holes are given by the simple equation:

$$T = \frac{\kappa}{2\pi},$$

Equation 34 : Temperature of a black hole

where t is the temperature and κ is just the surface gravity of the black hole. The surface gravity is a way of expressing acceleration due to gravity at the event horizon, but in strange units. Let us skip the lengthy derivation for a Schwarzschild black hole, and get right to the result. The surface gravity of a black hole is:

$$\kappa = \frac{1}{4M}$$

Equation 35 : Surface gravity of a black hole

The surface gravity is inversely proportional to the mass of a black hole. Therefore, small black holes have high surface gravities, and big black holes have small surface gravities. This will become important shortly.

Since we can now calculate the temperature and entropy of a black hole, we can reconsider the meaning of the thermodynamical laws that got us here. In black hole physics, the four laws of thermodynamics can be restated as they apply to black holes like this:

5.4 Restated Thermodynamic Laws

The zeroth law states that a black hole's surface gravity is the same across its surface. While gravity and temperature are different things, they are very closely related in black hole physics.

The first law states that changes to a black hole depend on the mass and energy consumed by the black hole. This is a statement of energy conservation.

The second law states that the area of a black hole always increases as matter falls in. The event horizon can shrink when Hawking radiation is emitted. However, there is a generalized second law that states that the sum of the area of the black hole and the entropy of the emitted Hawking radiation always increases.

Now that we have a theory of black holes compatible with the laws of thermodynamics, what can we say about them that we did not know before?

Simply, black holes have well-defined temperatures and well-defined entropies. Therefore, a black hole has temperature.

What? Did you notice how the mass of the black hole relates to its temperature?

This is where things get strange. The more massive a black hole is the colder it becomes, and the opposite is true too, the smaller a black hole is the hotter it becomes. Now that is strange. To calculate the temperature of a Schwarzschild black hole, this is the full equation:

$$T = \frac{\hbar c^3}{8\pi G M k_B}$$

Equation 36 : Temperature of a Schwarzschild black hole

Using this equation with a one solar mass black hole yields a chilling temperature of 60 nK. That is closer to absolute zero than most scientists have been able to achieve in the lab. The lowest recorded temperature of anything on Earth was a molecular gas created here at the 'University of Alberta' by Professor Lindsay LeBlanc, at a mere 40 nK, that is 20 nK colder than a solar mass sized black hole.

How small do you think a black hole would need to be for it to be room temperature? What would happen as a black hole cools off through Hawking radiation?

6 Lifespan of a Black Hole

Quantum mechanics tells us that we cannot know exactly where a particle is located. In particular, it could be located at any position within its DeBroglie wavelength. If the DeBroglie wavelength of a particle is larger than the size of the event horizon, then there is no reason to think that it is actually inside of the black hole.

6.1 Quantum Tunneling

Quantum mechanics tells us that due to the wave nature of particles, mass that has fallen into the black hole can potentially get out. This concept is called quantum tunneling and leads to the process of Hawking radiation.

Stephen Hawking calculated the probabilities for particles escaping from a black hole. Hawking showed that the number of particles with various energies that escape from a black hole corresponds to exactly the same emission as blackbody radiation. Therefore, Hawking proved that black holes are actually blackbody emitters. Very cold blackbody emitters, but still this was a rather surprising result.

If an object is hot and emits as a blackbody this means that it has a temperature. We learned earlier in this course that a hot object's temperature is inversely related to the peak wavelength through Wien's law. The peak wavelength is the wavelength where the most particles, or photons, are emitted. Wien's law is:

$$T = \frac{W}{\lambda_{peak}}$$

We know if the peak wavelength is red, corresponding to 700 nm, the temperature of the object is 4100 K. If the wavelength is longer in the IR, or radial parts of the electromagnetic spectrum, then the temperature will be cooler.

What would be the temperature of a black hole?

We already know the event horizon radius of a one solar mass black hole is 3 km. A hot object whose peak wavelength is this large has a very small temperature, which we saw in the last section is 60 nK. A lower mass black hole will have a smaller event horizon. Therefore, the emitted Hawking radiation will have a smaller peak wavelength. Smaller peak wavelength means higher temperature. This leads to the inverse relationship between black hole mass and temperature.

Where does the energy for this radiation come from?

The energy is coming from the mass of the black hole. The process of Hawking radiation slowly converts the mass of the black hole into energy by allowing the mass to leak out of the black hole. The Hawking radiation that the black hole emits is blackbody radiation, which has no dependence on the composition of the material that originally fell into the black hole. The emitted Hawking radiation depends only on the black hole's mass and angular momentum. Therefore, it preserves the no-hair property of black holes. This is another aspect of the black hole information paradox. The emitted radiation does not convey any of the information that had previously been captured by the black hole.

Hawking radiation is a quantum mechanical process that allows mass to slowly leak out of the black hole's event horizon into the region outside. If a black hole loses mass, we know that its event horizon must shrink. Shrinking the event horizon means that the temperature will increase. Since higher temperature, hot objects are also brighter, this means that the rate that mass is lost will increase. Therefore, as black holes lose mass and become smaller, they also radiate faster. This could get messy.

6.2 Black Hole Evaporation

The result that Hawking radiation causes a black hole to lose mass is called 'Black Hole Evaporation.' If you were to extrapolate down to zero mass, the equations would predict infinite brightness and temperature. This extrapolation is most likely not correct and requires a quantum theory of gravity to predict the outcome correctly. One possibility is that all of the information that was lost inside the black hole is finally released in the moments before the Hawking radiation process is finished.

The process of black hole evaporation takes a long time for the black holes that we see in nature, but is rapid for black holes with tiny mass. For instance, the black hole Cygnus X--1 would take 10^{68} years to evaporate. That is an enormous amount of time, longer than the present age of the Universe by a factor of an octodecillion, which is a one followed by 57 zero's.

Since Cygnus X-1 will not evaporate anytime soon, the Hawking radiation plays an important role in its lifespan. In addition, Cygnus X-1 is accreting mass from its companion. Therefore, it is gaining mass at a much faster rate than the black hole evaporation rate. The X-rays emitted by the accretion disk are enormously bright in comparison to the Hawking radiation making it impossible to detect the faint signal from the black holes evaporation.

At present, Hawking radiation has never been detected from any black hole. This is due to the very long wavelength associated with it, and the very low temperature and energy associated with astrophysical black holes. In order to detect Hawking radiation, we need to hunt for a special set of circumstances. First of all, it would be best to look for an isolated black hole that is not accreting matter from a companion star. Secondly, the mass should be very small, therefore, that the temperature is high enough that we could detect it.

How small should the mass be?

If we could find a black hole with the mass the same as our Moon, then the Hawking radiation would be 1.6 K, which would be difficult but possible to measure. Any black hole with a mass smaller than our Moon would be hotter and easier to detect.

If we want to see the whole evaporation process, it would be convenient if the time for the evaporation to take place would be less than the present age of the Universe, which is 13,800,000,000 years. A black hole with a much smaller mass, such as 10^{12} kg or smaller, would take less than 13,800,000,000 years to evaporate. That might sound like a large mass, but 10^{12} kg is approximately just the mass of a large mountain here on Earth. That may still sound like a large mass, but to astrophysicists that is tiny.

Unfortunately, we do not know about any mechanisms for creating mountain-mass black holes from astrophysical objects like stars, or planets, or asteroids.

6.3 Primordial Black Hole

One possibility is that very small black holes, called primordial black holes, could have been created in the Big Bang. However, no evidence for Hawking radiation from these conjectured primordial black holes has ever been seen. If you are really interested in detecting Hawking radiation, you will have to create artificially your own black hole by smashing protons and antiprotons together at incredible speed.

Making your own black hole sounds somewhat silly.

Would it not be dangerous to create a black hole on Earth?

Well, we just learned that small black holes evaporate quickly by emitting Hawking radiation; therefore, if it is a really tiny one, it will not last long enough to capture matter from the Earth. It is theoretically possible to create one using a particle accelerator such as the 'Large Hadron Collider,' also known as the LHC, located in Geneva, Switzerland. The LHC accelerates protons and antiprotons in opposite directions along a circular path.

When the particles are moving fast enough, the proton and anti-proton beams are crossed and allowed to smash into each other. If the proton and anti-proton get closer together than the Schwarzschild radius for two protons, they could form a tiny black hole before they get a chance to annihilate each other. The tiny black holes formed in the LHC would evaporate very quickly in much less than a second, and we could then observe the energy released. Scientists are looking for the signature of the energy released from Hawking radiation, but so far, no evidence for black holes created in the LHC has been found.

We should remember that the Earth's atmosphere is bombarded by natural high-energy particles called cosmic rays that possibly originate from the jets of supermassive black holes in faraway galaxies. Some of these cosmic rays could interact with atoms in the Earth's atmosphere and create a tiny black hole. No evidence for this process has ever been seen. This tells us that either tiny black holes are difficult to create, or when they are created the radiation that they emit is difficult to detect.

Some people expressed concern about the possible harm to the Earth if a tiny black hole were created in the LHC. However, the very short lifetime due to Hawking radiation would make these tiny black holes harmless. In addition, in the five billion years of the Earth's history, no cosmic ray collision, which could be more energetic than the LHC, has ever created a black hole that has harmed the Earth.

We also had not seen any other planets or stars harmed by interactions with tiny black holes. Therefore, there is no evidence of risk. Physicists who study these tiny black holes are confident that their existence does not endanger life on Earth.

7 Summary

Over the last few lessons, we have journeyed to the black hole Cygnus X-1 to explore the black hole binary system, and see the wondrous sights outside the event horizon. We then dove inside to explore the mysteries hidden behind the event horizon. We learned that the boundary between the inside and outside of a black hole is actually rather fuzzy, once we include the laws of quantum physics. In fact, quantum mechanics suggests that black holes are not actually black, and they can actually leak out their contents and eventually disappear.

Illustration 100 : CHANDRA X-ray observatory

Scientists today have different levels of understanding of the phenomena associated with black holes. First of all, there is excellent evidence that black holes do exist. The fundamental characteristics of a black hole, such as the location and properties of the event horizon, the ISCO, spacial curvature, and time dilation, are well understood and are no longer controversial. We see excellent evidence of jets, accretion disks, and many features of accretion in many black hole systems. However, we do not yet have a full understanding of all of these processes. Thankfully, we have many telescopes observing these systems, and we are building a very good understanding of these structures, which we will begin to explore more in the next few lessons.

Crossing through the event horizon, we enter a region where it is predicted to be impossible for light or anything else to escape. Therefore, we have no observational confirmation of the mathematical theories describing the interior. However, as long as we do not include quantum physics, it is possible to write out all of the equations describing the inside of a black hole, including the singularity.

Quantum mechanics, the science of the very small, and how it applies to black holes is still a big open question. Since quantum mechanics is normally only important for describing small objects, the introduction of the ideas of quantum physics mainly only affects tiny black holes. For the smallest black holes, we cannot be certain whether particles are inside or outside of the event horizon. This leads to the prediction of Hawking radiation, which culminates in the evaporation of a black hole.

A related problem is that of information.

Is it truly destroyed when it enters the black hole?

This is a question many astronomical theorists are still pondering.

However, we should remember that quantum mechanics is probably also important if we want to understand the singularity of all black holes, whether or not they are small. Addressing questions, such as the properties of the singularity, information loss, and the final result of black hole evaporation, will require physics that has not yet been uncovered, a quantum theory of gravity. There are only hints of what a quantum theory of gravity might look like, but full details are beyond our present understanding.

Now that we have explored some really big unknowns, it is time to look more closely at all the really cool phenomena that we can see when we point our telescopes at black holes.

Hunting For Black Holes

1 Introduction: Hiding In Plain Sight

In order to find black holes, scientists need to choose the appropriate tools. Of course, we cannot yet travel to a black hole, but what we can do is collect light from the structures around a black hole. In order to choose the right tools, we need a better understanding of the light that is emitted from a black hole, and from the structures in its neighborhood. The structures near a black hole can emit light in parts of the electromagnetic spectrum, ranging from the lowest energy radio waves, to visible light, to high energy X-rays. We need to choose the right type of telescope that will allow us to view the light emitted from black holes. Let us begin by discussing optical telescopes.

2 Telescopes

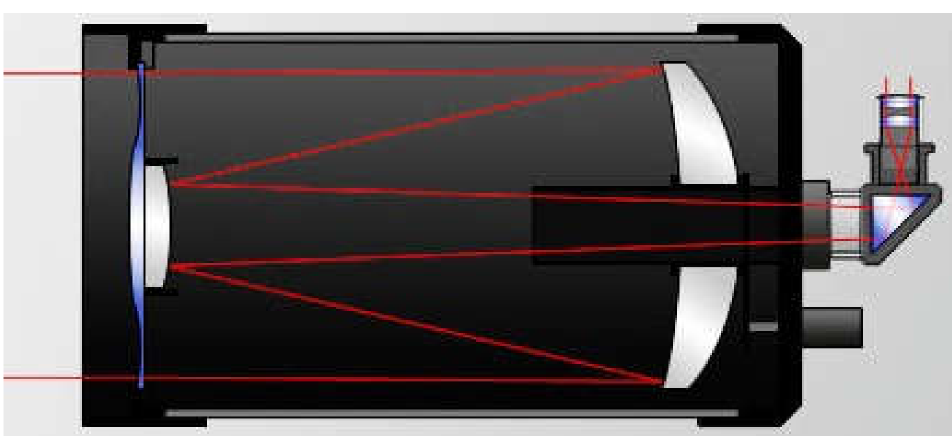
You want to find a black hole. Let us get started by evaluating some of the tools available to us.

Obviously, when astrophysicists study objects in the sky, they typically use telescopes. Telescopes allow us to collect light and produce images of the features near a black hole. However, there are many different types of telescopes, therefore, it is important to choose the best one in order to be certain that what you are in fact looking at is a black hole.

2.1 Reflecting Telescopes

You may have seen a telescope like this one that we have at the 'University of Alberta's Observatory.' This is a fairly standard type of telescope that gathers and focuses light using curved mirrors called a refracting telescope. Historically, it was much easier to make lenses rather than mirrors. Therefore, early telescopes, like the ones used by Galileo used to discover the moons of Jupiter, are called refracting telescopes. In modern times, it is much easier to build large mirrors than it is to build large lenses. Therefore, the enormous telescopes used in astrophysical research are reflecting telescopes.

2.2 Schmidt-Cassegrain Telescope



When we talk about ground-based reflecting telescopes, the majority collect light in the optical spectrum. That is the light, which humans can see with their eyes. For example, this Schmidt Cassegrain telescope has two mirrors: a big primary mirror at the back, and a secondary mirror at the front. It also has a corrective lens, but this is quite an expensive telescope.

The purpose of a telescope's primary mirror is to collect as much light as possible from faint objects. The larger the diameter of the mirror, the lighter is collected. Think of it like a big bucket. It becomes easier to see faint celestial bodies, but a larger mirror also means a larger, more expensive telescope, which is a trade off that we have to pay in order to get better resolution of distant objects. For example, if something looks like a blurry smudge through a small telescope, a bigger telescope will produce a clear image without changing the magnification. Larger telescopes may also allow for more magnification, but magnification should be second to the mirror diameter. Dim and distant astrophysical objects, like nebula and galaxies, are easily resolved by small telescopes with low magnification, but they require lots of light in order to be visible.

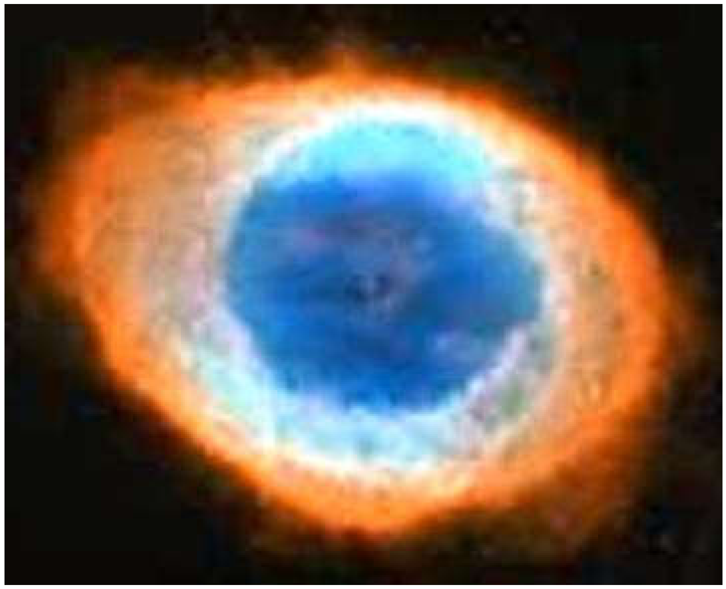


Illustration 101 : Ring nebula in the Lyra constellation

My family invested in a 4 in Newtonian reflector when I was young. It was a present from my dad. This telescope encouraged my interest in astronomy, and it taught me an important lesson. If you are purchasing a telescope, do not purchase one that advertises it is magnification. This is a sign of a poor-quality telescope. Instead, a good-quality telescope is described by the diameter of the primary mirror, or for a refracting telescope the diameter of the primary lens. For instance, our telescope at the 'University of Alberta' has a huge 14 in diameter mirror. Sorry about the imperial units, they are still common among telescope manufacturers. The 14 in mirror can collect much more light than smaller telescopes revealing dim structures in the night sky like the Ring nebula in the constellation of Lyra.

Illustration 102 : Gemini telescope

Large ground-based research telescopes like the two Gemini telescopes in Chile and Hawaii have mirrors that are 8 m in diameter. However, that is a drop in the bucket compared to some ongoing construction projects like the extremely large telescope or ELT, which will have the largest compound mirror of any telescope in history.

2.3 Independent Motion Adaptive Optics

Illustration 103 : ELT

The ELT's compound mirror will have an effective diameter of 39 m. It is self-made up of a collection of smaller mirrors that can be aimed independently. Scientists call this independent motion adaptive optics, because the mirrors need to move in order to cancel out the turbulence of Earth's atmosphere. Often, they measure these disturbances using powerful lasers.

Illustration 104 : Subaru telescope

Here is the Subaru telescope, calibrating his optics. The Earth's atmosphere is turbulent, and the rapid motion of air pockets in the atmosphere smears out the light from stars, which makes them appear blurry.

What would be the best place to construct these massive telescopes?

Of course, you would want to build them near the top of a mountain. This is not to get them closer to the stars. By situating the telescope on the top of a mountain, we decrease the amount of atmosphere between the telescope and the stars, which improves the seeing. Seeing is actually a technical term used by astronomers. If the atmosphere is calm, and the images seen through the telescope are crisp and steady, we say the seeing is good tonight. There is an obvious way to avoid the blurring effects of Earth's atmosphere. Launch a telescope into space.

Of course, you are probably already familiar with the Hubble space telescope, but did you know about its successor, the James Webb space telescope?

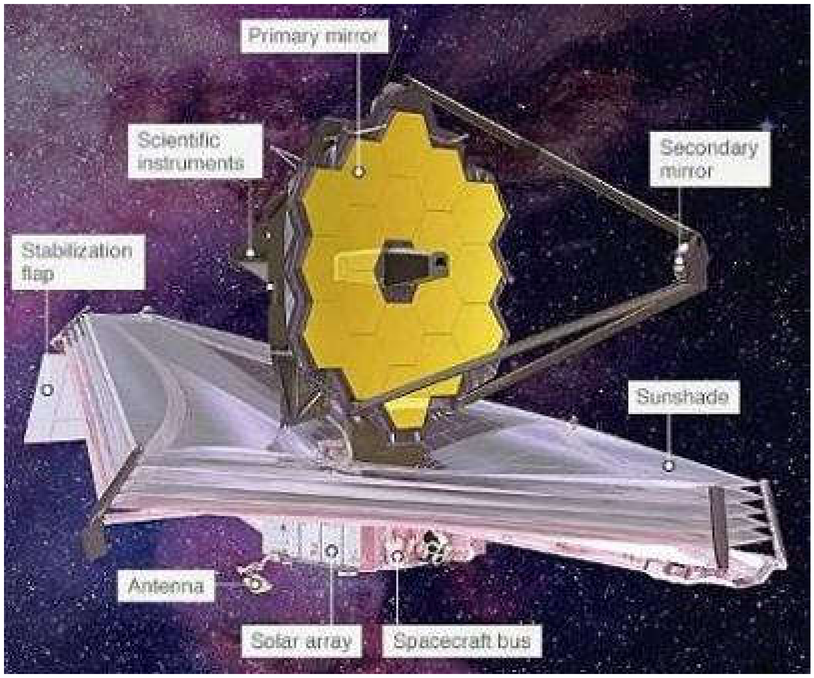


Illustration 105 : James Webb telescope

The telescopes that we have just looked at are all visible light telescopes, also called optical telescopes. These are telescopes that can detect light visible to our eyes along with some neighboring wavelengths in the IR- and UV-light. This type of telescope is capable of viewing stellar companions of black hole binary systems. However, since most of the energy emitted by a black hole is in parts of the electromagnetic spectrum that our eyes cannot see, we need to investigate other types of telescopes capable of detecting light that is invisible to our biological eyes.

2.4 Radio Telescopes

Black hole jets emit radio waves, part of the spectrum emitted by hot plasma within the jet. Therefore, a radio telescope is an important tool for black hole astronomers. Remember that radio waves are the lowest energy and thus the longest wavelength part of the electromagnetic spectrum. Since radio waves are electromagnetic waves, or photons, they still travel from the black hole towards us at the speed of light.

Radio waves have long wavelengths that range from mm to m in length, which is the reason why radio antennas have to be very long. You might be familiar with radio waves that you receive when listening to a radio station. For example, if you were listening to a station at 102.9 on the dial, meaning that you are capturing photons with frequencies of 102.9 MHz. They would have a wavelength of approximately 2.92 m. Recall, a green laser have tiny wavelengths, measured around 532 nm.

Illustration 106 : Very large array at San Agustin (New Mexico)

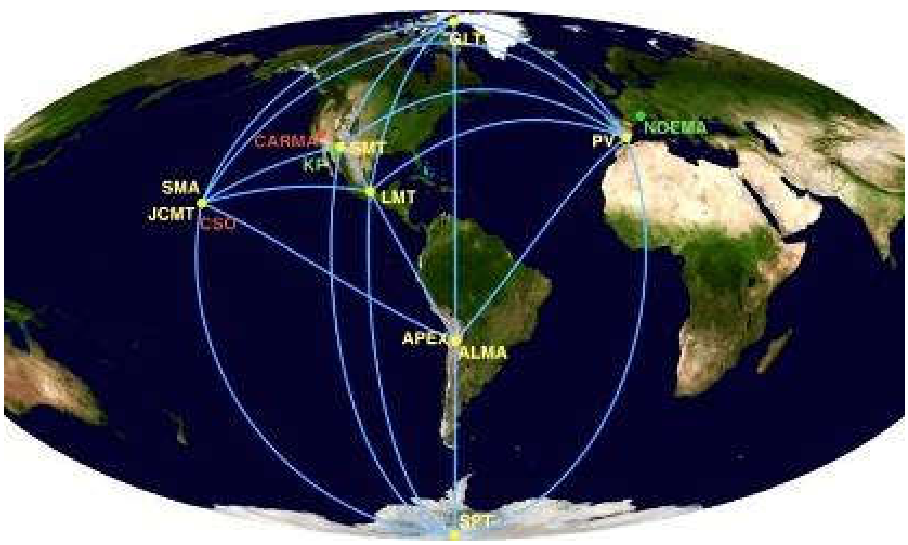
2.4.1 Interferometry

Radio telescopes like the ones that make up the very large array, which was featured in the movie 'Contact,' are usually large dishes instead of antenna. Radio waves from neighboring radio telescopes in an array can be combined using a technique called interferometry, which allows the whole group of telescopes to act as one large one. The effective size of a radio array is similar in size to the distance between the dishes.

Illustration 107 : 'FAST' Telescope (China)

The largest single-dish telescope called 'FAST,' the 500 m aperture spherical telescope is 500 m in diameter and located in China. If you have seen the James Bond movie 'Golden Eye,' you might recognize the Arecibo radio telescope in Puerto Rico where Bond defeats Stravalion.

2.4.2 Event Horizon Telescope



Radio telescopes located at different parts of the Earth as shown on this map are being used as one Earth-sized radio telescope called the 'Event Horizon Telescope.' It is observing Sagittarius A*, the supermassive black hole at the center of our galaxy. We will discuss the event horizon telescopes observations in one of our last lessons.

2.5 X-Ray Telescope

On the other end of the electromagnetic spectrum at high energies, black hole accretion disks produce X-rays. An X-ray telescope would be the best tool in our hunt for black holes, but there is one problem, Earth's atmosphere absorbs X-rays. Actually, that is a really good feature for our atmosphere. If X-rays could make it through the atmosphere to the ground, we would constantly be irradiated.

X-rays have even more energy than UV-light, the light that causes sunburns. Therefore, tanning under the X-ray light from a black hole would burn you crispy. Do not worry though, X-rays used in doctor offices and dentist offices are produced in safe quantities. Radiation therapies used to treat cancers are a good example of the damage X-rays can do, to the cancers of course. Since the Earth's atmosphere protects us from cosmic X-rays, an X-ray telescope needs to be launched above the atmosphere and into space.

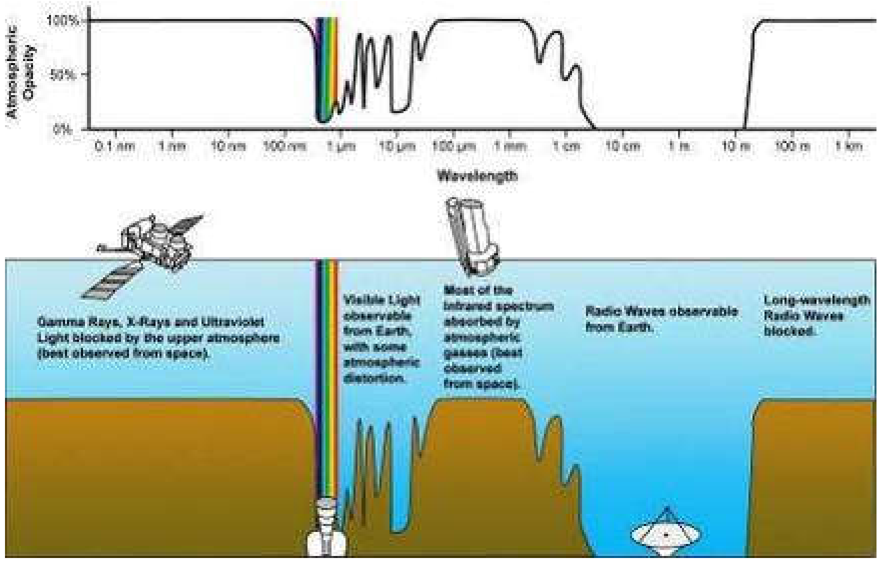


Illustration 108 : Atmospheric opacity

This diagram shows how much of the Earth's atmosphere blocks light with different wavelengths. Visible light and radio waves can penetrate through the Earth's atmosphere. However, γ-rays, X-rays, UV-, and IR-radiation are blocked by the atmosphere. Therefore, telescopes that can observe light at these wavelengths usually orbit the Earth.

The CHANDRA X-ray telescope is an important black hole detecting telescope. It allows astronomers to view X-ray images and spectra of black holes. CHANDRA is named after the Indian physicists Chandrasekhar, who is famous for his theoretical work on black holes, neutron stars, and white dwarf stars. He also prefers to be called CHANDRA.

Illustration 109 : XMM-Newton telescope

Another orbiting X-ray telescope is called the XMM-Newton. Although, CHANDRA is a better telescope for creating detailed X-ray images, XMM-Newton is a better telescope for determining the wavelength of those X-rays.

Illustration 110 : Athena telescope (Artist illustration)

A new telescope called Athena, with a planned launch date in the year 2028, will combine the best features of these two telescopes.

Illustration 111 : Nustar telescope

Nustar is another X-ray telescope that orbits the Earth, but the long length of this telescope allows astronomers to view much higher energy X-ray photons than the CHANDRA observatory. This allows Nustar to detect processes taking place very close to the black holes event horizon.

Illustration 112 : Nicer telescope on the ISS

A nice X-ray telescope called Nicer was recently mounted on the ISS, and it is orbiting the Earth on the ISS. Nicer is designed to give accurately the time of every X-ray photon that strikes it. This allows Nicer to detect rapid changes in X-rays that are emitted by black holes and neutron stars. Astronomy that makes use of the accurate photon timing is sometimes called time domain astronomy. This is just a small selection of some of the telescopes that are used to study black holes. A completely different way to detect a black hole is through gravitational radiation. Of course, we will learn more about gravitational radiation in a later lesson.

3 Chopping Up Rainbows

Have you ever wondered how we can determine so much about objects in the Universe, like the Sun? How do we know that it is made up of 74 % of H, that its surface temperature is almost 6,000 K, or that the Sun rotates once every 24.5 days?

3.1 Spectroscopy

The answers to all these questions in some way can be tied to a field of science called spectroscopy, which is the study of light and its interactions with matter. When a scientist observes and records light, they produce a spectrum or many spectra, which tell them how much of each color or wavelength of light is produced by the objects they are studying. When astronomers produces a spectrum, they are spreading incoming light into a band of colors, just as you see when light from the Sun is spread into a rainbow.

This is exactly Newton's famous prism experiment, where he demonstrated that white light is actually a combination of every color of the rainbow. An astronomer collecting spectral data is doing much the same thing, the act of separating light into its component colors, only modern equipment use special instruments called diffraction gratings.

3.1.1 Diffraction Grating

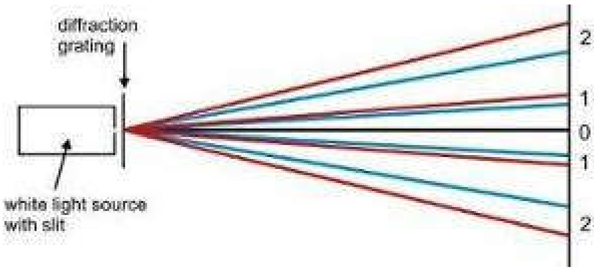
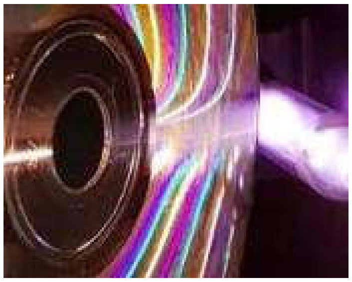


Illustration 113 : Diffraction grating

Just like Newton's prism, a diffraction grating separates light into its component colors. However, diffraction gratings use the physics of waves to spread light out instead of refraction.

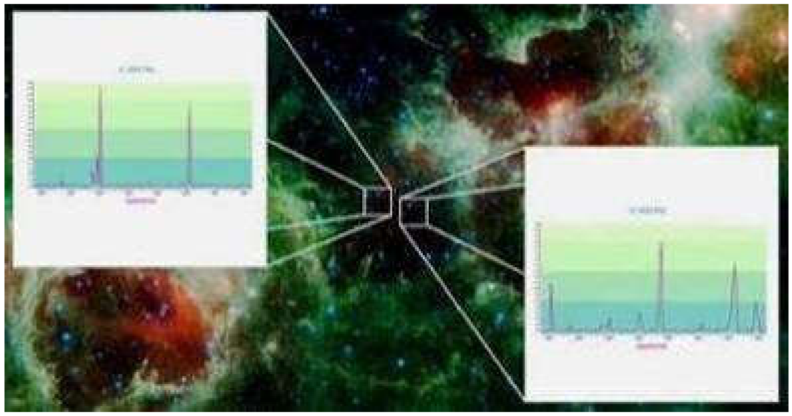


An example of this is the interference on a compact disc. The rainbows produced are from the interference of light rays reflected by the lines etched on a CD-surface.

3.2 Imaging Spectroscopy

Spectrometers can be combined with telescope technology for use in astrophysics. Telescopes equipped with spectrometers can do what is called imaging spectroscopy. By collecting a spectrum for each pixel of an image, scientist can distinguish what colors are produced in different locations on the same object.

3.2.1 Spectral Image



A spectral image is a type of image that allows us to do very special things. Even two regions, which look the same to our eyes, if we examine their spectra, overlaid on one another, there can be noticeable and important differences.

3.2.2 Extended Source

From a spectral image, we can extract a wealth of information about different parts of astrophysical objects. Since each pixel corresponds to a different location in the sky, we can examine all the different parts of what we call extended sources. An extended source is something that does not appear point-like to us. They extend over region of the sky. Extended sources appear to be large either because they are big, or because they are very close to us. Some examples of extended sources are the Sun, a nebula, or even a galaxy.

Spectroscopy is one of the most frequently used tools in an astronomer's toolbox. Without spectroscopy, we would struggle to define important characteristics of the objects we view; speeds, temperatures, and compositions, to name a few.

3.3 Spectrum

When matter in outer space interacts with light, we see the results as a spectrum. In astrophysics, we discussed three primary types of spectra, summarized by Kirchhoff's three spectral laws.

3.3.1 Kirchhoff's Three Spectral Laws

The first of Kirchhoff's laws describe the conditions for blackbody emission, while the other two laws deal with atomic emission and atomic absorption, which we will cover in the next lesson.

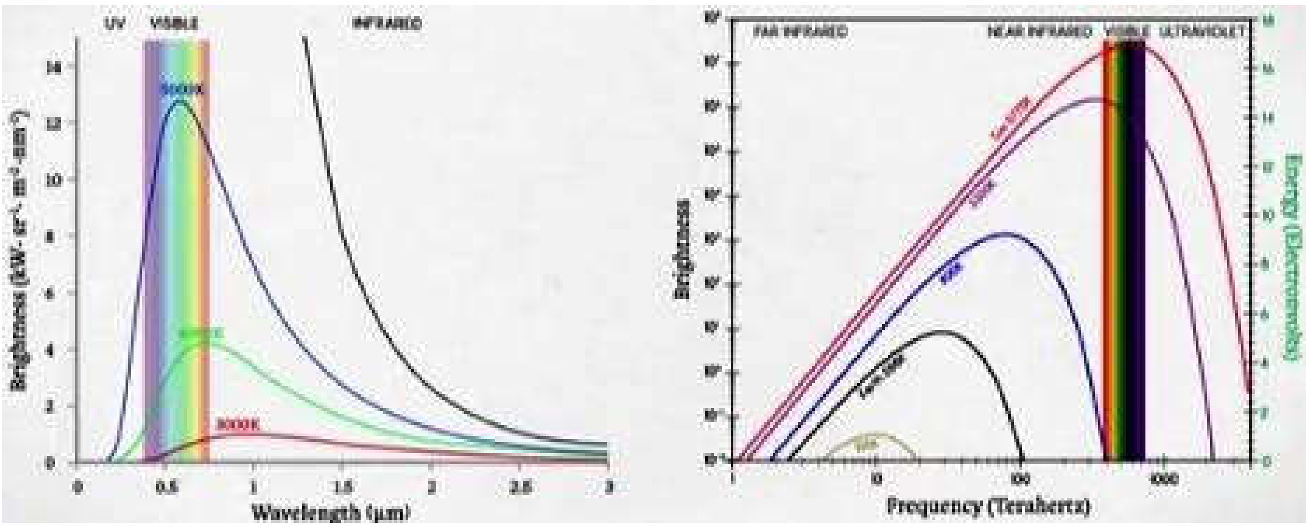
Kirchhoff's first law states that a luminous solid, liquid, or gas emits light at all wavelengths. This law is a description of the type of light given off by blackbody emitters. You are probably familiar with at least one type of blackbody emitter, your kitchen stove. If it has electric coil burners, like mine does, it will emit a deep red light when you are cooking. This might be confusing, since Kirchhoff's law says it should emit light of all wavelengths. Well, blackbodies do emit light of all wavelengths just at vastly different intensities. For example, there are so few X-rays being emitted at this temperature that we can totally ignore that part of the spectrum. On the other end, the burner feels hot, because along with a lot of red light, the burner is also emitting plenty of IR-light.

Color	Example	Surface Temperature(K)
	Spica (Virgo)	28,000 – 11,000
	Vega (Lyra)	11,000 – 7,500
	Sun	6,000 – 6,000
	Arcturus(Bootes)	5,000 – 3,600
	Antares (Scorpius)	3,600 – 2,000

Illustration 114 : Star color & temperature

The spectra of thermal or blackbody emitters are continuous, like rainbows. You may remember from a former lesson that blackbodies absorb all incoming light across all wavelengths and are completely non-reflective. The kind of light they emit will depend solely on their temperature. This temperature effect can be seen when examining a fire poker, as it gets hotter and hotter. First, there is red hot, then orange and yellow hot and finally white hot. The surfaces of stars, which are close approximations to black bodies, exhibit the same properties. Though they can get even hotter, getting to blue hot for certain types of stars.

As the thermal emitter gets hotter, its peak emission is shifted into more energetic regions of the electromagnetic spectrum. Black hole accretion disks can be so hot that their peak emission is not blue hot, it is not UV hot, and it is X-ray hot.



When plotted, black body spectra are smooth continuous curves that look like the hill of a roller coaster. Let us see how changing the temperature of a black body emitter changes its spectrum. Two laws govern the shape of a blackbody spectrum. First, Stefan-Boltzmann law states that a hotter object emits more light at every wavelength.

What does this mean for our plot?

Well, higher temperature, larger curve. Additionally, the second law, Wien's law, states that a hotter object emits light with greater average energy.

What does this mean for our plot?

A change in temperature will skew the peak of this graph. Hotter objects move the peak toward shorter wavelengths, higher energies, and lower temperatures move the peak towards longer wavelength, lower energies. Recall that frequency and wavelength are inversely related. Therefore, the same graph, plotted for frequency instead of wavelength, will look reversed. A higher temperature means that peak emission of a hotter object is shifted right towards higher frequency, which is more energetic.

3.4 Emission / Absorption Spectra

Kirchhoff's second and third laws are concerned with how emission and absorption spectra are produced. Producing these types of spectra relies on a process, which affects individual atoms and molecules called luminescence.

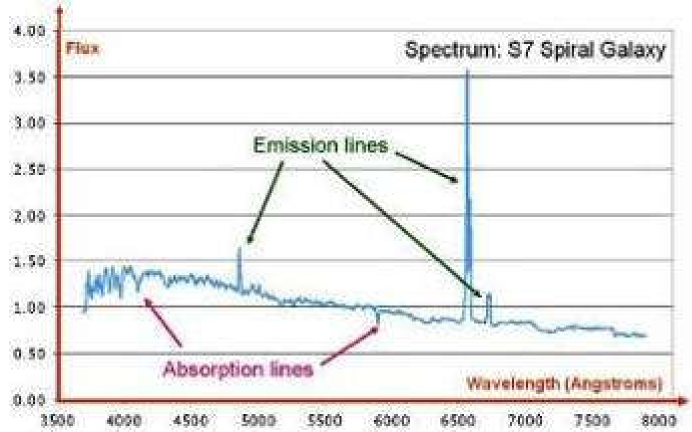
3.4.1 Luminescence

Luminescence is the process that produces light when electrons drop from higher energy states, within an atom or molecule, to lower energy states. Kirchhoff's second law states that a low-density hot gas seen against a cooler background emits a bright line or emission line spectrum. As we mentioned before, luminescence is responsible for this. When electrons transition from higher energy states to lower energy states, they emit light based on how far or how many states they drop.

The reverse process can also happen, which are described by Kirchhoff's third law. A low density, cool gas in front of a hotter source of a continuous spectrum creates a dark line or absorption spectrum. Therefore, if the right energy of light is shined through a low-density gas, like a nebula, electrons can steal energy from passing photons in order to climb to the higher energy states. By absorbing light, the low-density gas, cool gas, takes away portions of the continuous spectrum of the background emitter leaving behind dark absorption lines.

3.4.2 Energy Level Transitions

Energy level transitions are an effect of quantum mechanics. Electrons surrounding the nucleus of an atom are able only to accept quanta, or in other words specific amounts of energy. When a passing photon or a collision between atoms in a gas has the right amount of energy, the electron will transition to a higher energy state. Transitioning to a higher energy state is much like climbing a ladder. You can only exist at the top of each rung. You can attempt to place your foot in between the rungs, but all that will result in is a banged up shin.



Surely, after an electron transitions to higher energy, it spontaneously transitions back down to a lower energy state. The energy the electron had has to go somewhere, and what happens is the atom produces a photon, which has the same energy as the difference between the higher energy state and the lower energy state. A large number of these downward transitions will produce a bright emission line in the spectrum, and a large number of upward transitions will produce a dark absorption line.

3.5 Atom / Molecule Related Spectra

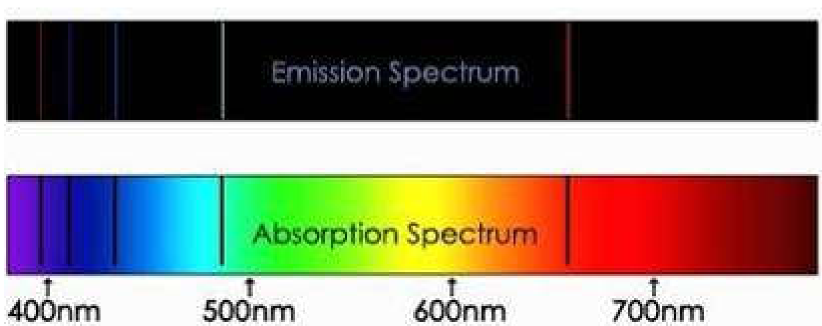
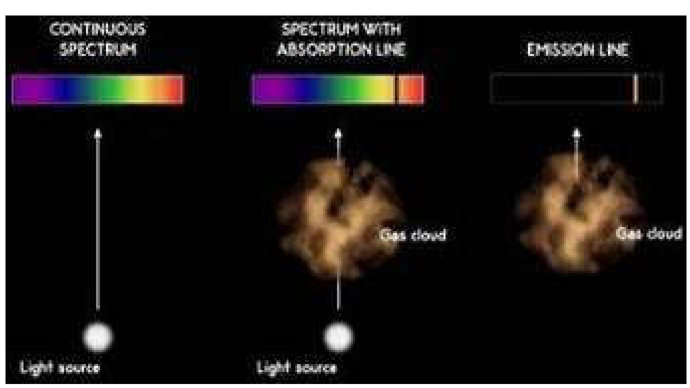


Illustration 115 : Spectra of Hydrogen

It is important to note now how we can determine chemical composition using emission and absorption spectra. Each type of atom or molecule has a unique set of energy levels, which produce a unique set of emission lines. Meaning, each type of atom or molecule can be characterized by a unique spectrum. This is a lot like fingerprints on your hand. Every person has a different set of fingerprints, and every type of atom produces a different emission and absorption spectrum. A lot of work has been done by scientists to study the spectra of atoms and molecules in the lab. Therefore, we know very well what they look like.



When we look at an object in the sky, we can match parts of its spectrum to specific atoms and molecules to determine of what it is composed. Here is a great diagram that helps us explain Kirchhoff's three laws. If a light source, like a star, shines through empty space, we see the black body spectrum it produces as a continuous rainbow of colors, like in the leftmost image.

If the star has a cooler outer atmosphere or photosphere, then some of the cold atoms will absorb photons with specific colors causing electrons to move to higher energy states. This removes light from the continuous spectrum of a background source creating an absorption spectrum, as shown in the center image.

If instead, light from a star strikes a nebula from the side, electrons will be excited and subsequently fall to lower energy states. In doing so, they will emit light with specific frequencies in all directions including ours. This process produces an emission spectrum like in the rightmost image.

Keep in mind that we are generalizing the emission and absorption processes, and that both can happen simultaneously, and are only mediated by the temperature of the object.

3.5.1 Determining Chemical Abundance

Both emission and absorption spectra are important in determining the chemical abundances of objects in space. We examine how bright emission lines are, or how dark absorption features are, and how each is associated with a different element or molecule to determine how much and what is prevalent in all sorts of astrophysical objects. This is the first step in characterizing a black hole system, but advanced techniques can tell us even more.

4 Advanced Illumination

To recap, we know that hot objects emit light by producing a continuous spectrum known as a black body spectrum. We know that low-density clouds of hot gas emit light at specific frequencies. We know that low-density clouds of cold gas in between hot sources and us absorb light at specific frequencies. Let us have a look again at a black hole system with an accretion disk.

Can you guess what kind of light we will see from the hot dense accretion disk?

If you said that accretion disks emit black body radiation, you would be correct. However, since accretion disks can become incredibly hot, that is millions of Kelvin, the peak wavelength, according to beams law, is not in the blue part of the spectrum, it is not even the UV. Accretion disks are so hot, that many of them have a peak wavelength in the X-ray part of the spectrum. We also previously learned that the black hole itself emits a type of radiation called Hawking radiation. Unfortunately, scientists have not yet measured any form of Hawking radiation, because the black body radiation from the accretion disks of black holes is phenomenally brighter than the light emitted through the Hawking process. In addition, the peak wavelength for hawking radiation emitted by a solar mass black hole would be a couple of 100 km long, which means that no radio telescope on Earth could detect it.

4.1 Synchrotron Radiation

We previously mentioned the magnetic fields around black holes, but we have not done much into the physics of their interactions with the matter and the black hole neighborhood. The reason is that magnetic fields around black holes are poorly understood how they are formed, how they are powered; and the effects they have on the light generated in the black hole environment. We do suspect that magnetic fields are responsible for boosting the energy of particles near a black hole by a process known as synchrotron radiation.

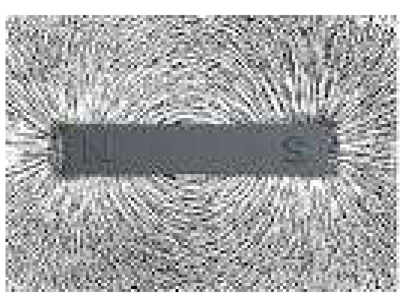
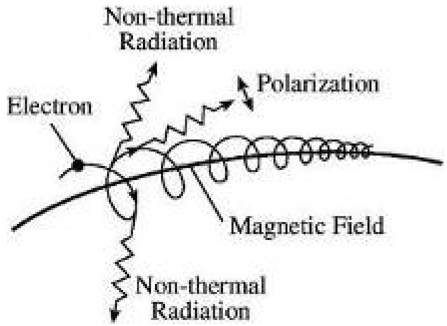


Illustration 116 : Magnetic field, shown by Fe --filings

A magnetic field exerts a force on electrons and magnetic materials like iron filings. We can easily see the effect of a bar magnets magnetic field on iron filings by bringing iron filings close to a bar magnet. The magnetic field forces the iron filings to move. They form a pattern that shows curves that stretch from the north and south magnetic poles. We call the lines that we see in these pattern magnetic lines of force.



An electron that moves across a magnetic field line feels a force that pushes the electron into a circular path around the magnetic field line. An electron that has some amount of momentum, also in the direction of the magnetic field line, will experience the same effect, but appear to be moving on a spiral path circulating around the magnetic field line.

Synchrotron radiation was first seen in laboratories that accelerate electrons. These laboratory accelerators are called synchrotrons. Therefore, when the radiation was first observed in 1947, it was called synchrotron radiation. One modern synchrotron is the Canadian light source located in Saskatoon, Saskatchewan, capable of producing some of the brightest light on Earth.

4.1.1 Beamed Radiation

Synchrotron radiation is produced when electrons travel in curved paths. Photons are emitted in the direction that the electron is traveling, like the headlights of a car going around a curve. I prefer to think about the screams produced on roller coasters. They are loudest during the tightest curves. Since spiraling electrons are moving so quickly, they will naturally emit high-energy photons due to the paths curvature. When radiation is emitted in one direction, we say that the radiation is beamed. This is very different from black body radiation, which is equally bright in all directions.

4.1.2 Isotropic Radiation

Radiation that is equally bright in all directions is called isotropic. Synchrotron radiation is generally associated with the beam emission in black hole jets, which we will discuss shortly. The brightness of the light emitted at different wavelengths depends on the strength of the magnetic field and the energy of the electrons.

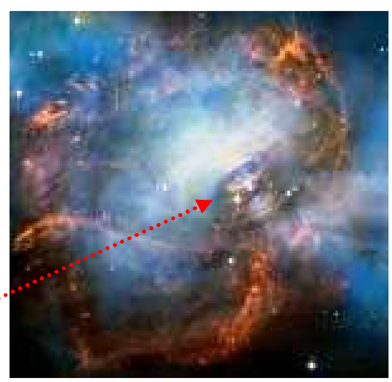


Illustration 117 : Crab nebula

One beautiful example of synchrotron radiation can be seen in this true color visible light image of the Crab nebula. The Crab nebula is a supernova remnant, which has, at its center, a type of neutron star called a pulsar. The pulsar is one of the bright white sources near the center of the image. The faint blue light in this image is created by synchrotron emission from electrons that have been accelerated by the neutron star’s strong magnetic field.

Depending on how fast the electrons are accelerated by the pulsar's magnetic field, synchrotron radiation can also produce light in the form of radio waves, X-rays, and even higher energy γ-rays. Because this image is only in visible light, we cannot see those forms of radiation. The red light in the image is an emission line spectrum coming from excited H-gas.

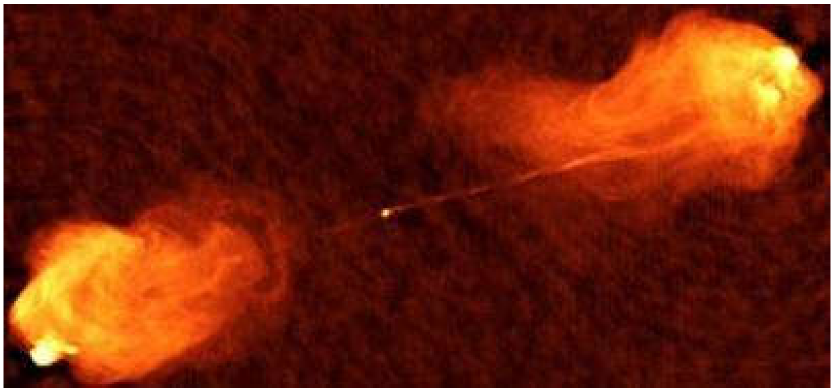


Illustration 118 : Cygnus A

This image of the radio galaxy Cygnus A, shows a bright point of light and two bright regions stretching out from the point of light to about 100,000 ly in opposite directions. The red color represents the radio emission, showing that the central point of light is the location of a super-massive black hole. The two bright regions are glowing due to electrons emitting synchrotron radiation.

4.2 Compton Scattering

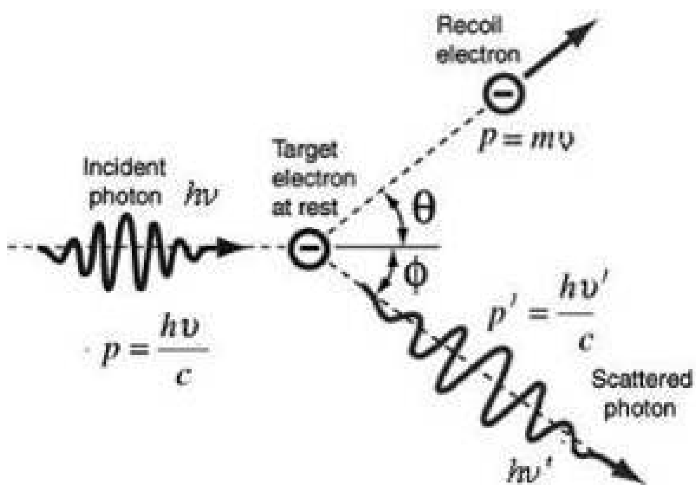
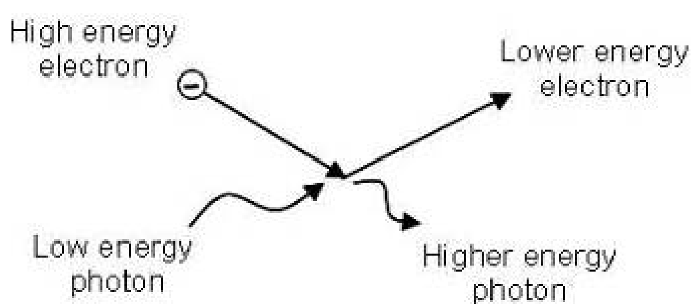


Illustration 119 : Compton scattering

Another process, which modifies the electromagnetic radiation present in the environment surrounding a black hole, is called Compton scattering. When high-energy photons, like X-rays scatter off electrons in a low-density gas, the photons can lose energy in the collision. In Compton scattering, photons collide with electrons as if billiard balls bouncing off one another on a pool table. After the collision, the electron and the photon move off in different directions, with the outgoing photon having lost energy to the electron. The photon, which has lost energy, travels away red-shifted with a longer wavelength and it started out with. Scattering of photons off electrons also takes place for other types of light. Not just X-ray photons like those that we have seen in our description of Compton scattering. For low energy photons, like the light visible to the human eye, the wavelength of the photons are much larger and quantum effects are less important. For visible light photons, the collision results in light changing his direction, but does not result in a change of color.

4.3 Inverse Compton Scattering



A similar process to Compton scattering called inverse Compton scattering, is well, exactly, the inverse of Compton scattering. Instead of a photon losing energy in a collision with an electron, inverse Compton scattering describes a process, which results in an increase in photon energy. When a photon collides with a high-energy electron, the electron gives some of its energy to the photon. This increases the energy of the photon resulting in a wavelength being blue-shifted. In order for inverse Compton scattering to take place, a source of electrons, which are moving close to the speed of light, is required. Regions near black holes, such as the corona, are places where inverse Compton scattering is likely to take place.

4.4 Synchrotron Self-Compton Emission

There are many more methods by which light can be emitted, absorbed, and shifted. Some processes, like synchrotron self-Compton emission, are combination of the ones we just covered. If electrons are spiraling around magnetic field lines at relativistic speeds and emitting synchrotron radiation, the photons emitted can then scatter off high energy electrons and gain even more energy. We know our audience loves learning about changes the light, but now we must move on to determine where in a black hole system these sorts of processes dominate.

5 Black Hole Disc

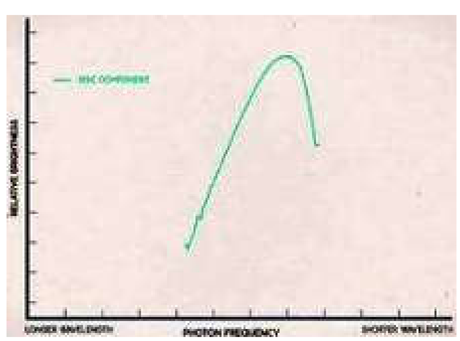
In this last lesson, we have explored how to look at black holes. Now, we get to the fun stuff. We get to see actually, what astronomers see. Let us examine the information received from black holes with various telescopes, and find out how astronomers use this information to learn more.

Active black hole binaries, like our friend, Cygnus X-1, are impressively bright in X-rays. Black hole binaries can be about 10^{10} times brighter than our Sun in X-rays; that is 10 billion times brighter. This means that in the X-ray part of the spectrum, black hole binaries really stand out.

Stellar mass black holes have two main features in the X-ray band. The first, we associate with the hot accretion disc. The material in the discs around stellar mass black holes is traveling so quickly that it can reach temperatures of millions of K, which means, that the peak of the disc's emission is in the X-rays.

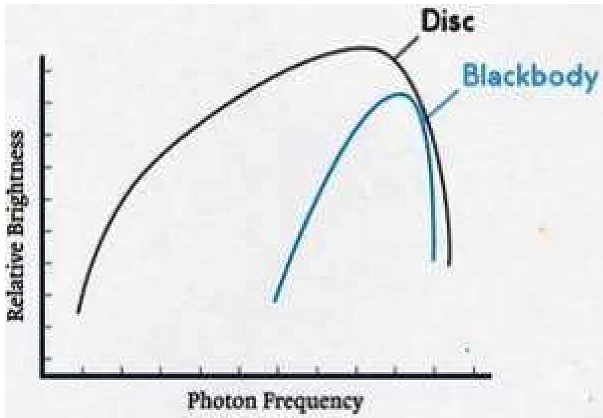
In an earlier lesson, we mentioned that the emission from the disc would be like of a blackbody, but what does a disc looks like in X-rays, and what can this tell us about the black hole?

The horizontal axis of this plot is photon frequency, which you may recall is inversely related to the wavelength of light. Therefore, as we move along the X-axis, from left to right, the photon frequency will increase. This increase in frequency means that the wavelength of light is getting shorter. The vertical, or Y-axis, is labeled relative brightness. The units of this axis are a little strange, and therefore, we have left them off. We do not really need to worry about them at this point though; all we need to remember is that things get brighter the further up the scale you go.



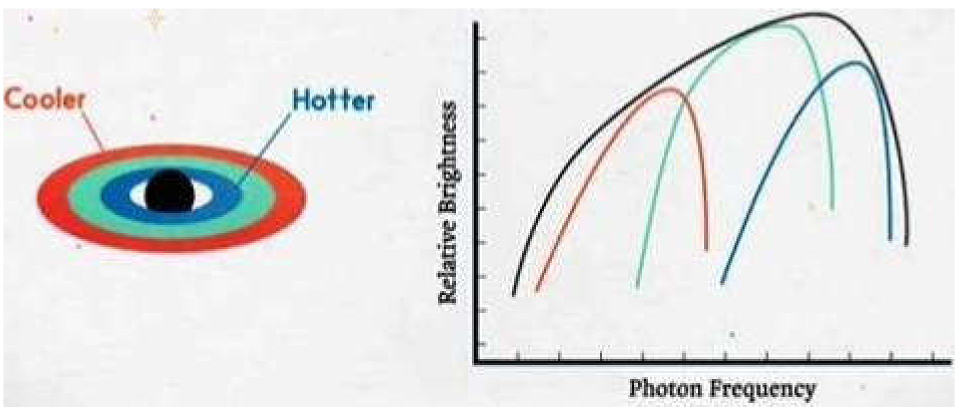
If we now look at the spectrum itself, we can see the feature, or the shape, astronomers have associated with the disc. It looks kind of like a hill. We have a steady slope building from lower photon frequencies, or longer wavelengths, up to a peak at higher photon frequencies, or shorter wavelengths. This steady slope is known as the tail of the disc. After the peak, there is a sharp drop-off, or turnover, towards higher photon energies. Astronomers call this feature a component of the spectrum, in the same way the disc is only part or a component of the black hole binary system.

What would cause this shape?



Well, the emission from the disc is thought to be powered by blackbody radiation. However, if we now plot a disc spectrum next to a black body spectrum, we can see that they do not quite match up.

How can this be?



The easiest way to think about this is to imagine that the disc is made up of a series of narrow rings. Each of these rings is emitting radiation at a different temperature. As we move inward through the disc, from ring to ring, each subsequent ring gets smaller and hotter. The hotter the ring, the more the peak of the spectrum becomes shifted towards higher photon frequencies.

Now do you see why the spectrum is not one blackbody spectrum?

5.1 Multi-Color Disc Model

If we plot a spectrum of each of these rings, and stack them all together, we get an overall shape that matches the observed spectrum of the disc. Astronomers call this the multi-color disc model, since each ring peaks at a different wavelength, or color, from the next.

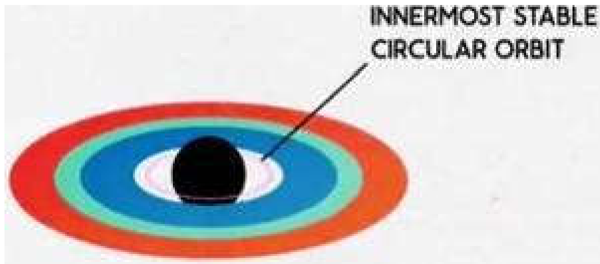
The multi-color disc model produces a close fit to observational data from accretion discs. While this model is simple, it is widely accepted by the astronomical community. It has been accepted because this model provides a reasonable description of the accretion disc emission and can provide key information relating to the black hole. The peak temperature of the multi-colored disc model tells you the peak temperature of the inner ring of the disc. If this last ring is at the ISCO around the black hole, then this temperature can give us information relating to the mass of the black hole.

However, we should note that many astronomers have used the multi-color disc model for decades and probably will continue to do so for a while to come, the simple model has some issues.

Why do we have these issues?

Well, it is at this point I should remind you that astronomy is different from many other areas of science. Most scientists come up with theories and then try to test them by looking at the objects they are investigating, by picking them up, by turning them around, by exploring things from all angles. Quite often, scientists can poke and prod things they are interested in, maybe even pull them apart and, hopefully, put them back together again. This is not the case in astronomy. All the objects astronomers investigate are out there in space. They are too far away for us to visit, yet, and therefore, we only have the small amount of light that they send in our direction to help us piece together their inner workings.

What are the problems with the multi-color disc model?

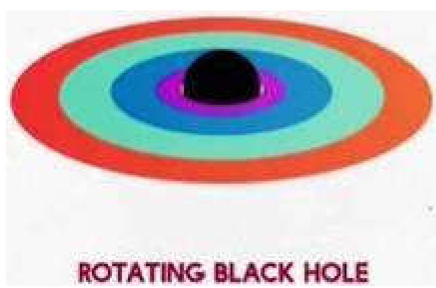


The first issue is that, in order for the temperature of the innermost string to provide information on the mass of the black hole, we have to work on the assumption that the black hole's accretion disc extends all the way down to the ISCO.

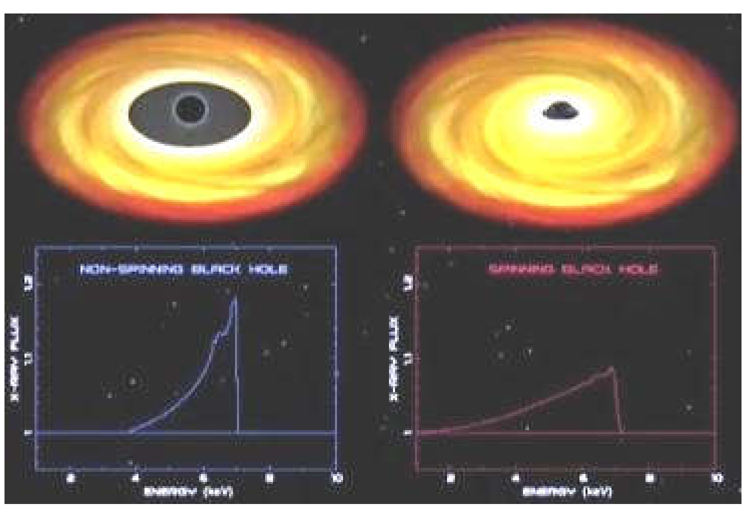
However, is this a safe assumption?

Even the nearest active black holes are so far away that we cannot directly image the inner disc. As such, we do not know how safe it is to assume the accretion disc extends all the way to the ISCO, but we suspect that it does when the disc spectrum dominates.

What other problems could there be with the multi-color disc model?



Secondly, this model does not take into account the spin of the black hole. As we saw in a further lesson, if the black hole is spinning, the ISCO can shrink from three times the Schwarzschild radius down to ½ the Schwarzschild radius. Therefore, for a given temperature, or radius, the spin of the black hole can change our estimate of the black hole's mass by up to a factor of six.



In order to overcome this issue, astronomers would need to know also the spin of the black hole. If the spin of the black hole is known, then astronomers will fold this into their mass calculations to improve our estimate of the black hole's mass. In most cases, however, we do not know how fast these objects are spinning. When we do not know the spin, astronomers tend to assume zero spin, knowing that this will add an additional error onto the estimate of the black hole's mass.

The final issue with the multi-color disc model is that it is a very simple model. This model does not take into account all of the physics of the accretion disc, the material in the disc is incredibly hot, and it is thought to be some kind of plasma. Plasmas have been found to act like fluids. It is also thought that there are magnetic fields threaded through the accretion disc. However, to account for these factors, you must perform very complex magneto-hydrodynamical calculations. These calculations usually require a few spare days, weeks, or even months even with the help of a supercomputer. Observers tend to leave these calculations to the theorists and continue to use their simple toy multi-color disc blackbody model when playing with their data.

As we mentioned earlier, black hole binaries, like our good friend Cygnus X-1, are bright in the X-ray portion of the electromagnetic spectrum. This is why astronomers often call these systems X-ray binaries. Their accretion disc spectra peak in the X-ray band of the electromagnetic spectrum with a tail extending through UV-waveband, and even into visible wavelengths.

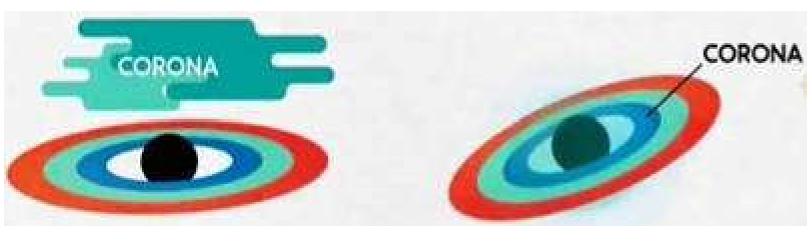
How would this change if we were to move up the mass scale of black holes, if we were to consider intermediate or even supermassive black holes?

Black holes that are more massive are larger. Both the event horizon and the ISCO are found at greater distances from the black hole singularity. This would mean that the innermost ring of the disc would be at a greater distance from the center of the black hole, and therefore, will be cooler. As cooler discs emit lower photon frequencies, the peak of the disc spectrum of a supermassive black hole would be in the UV-part of the spectrum.

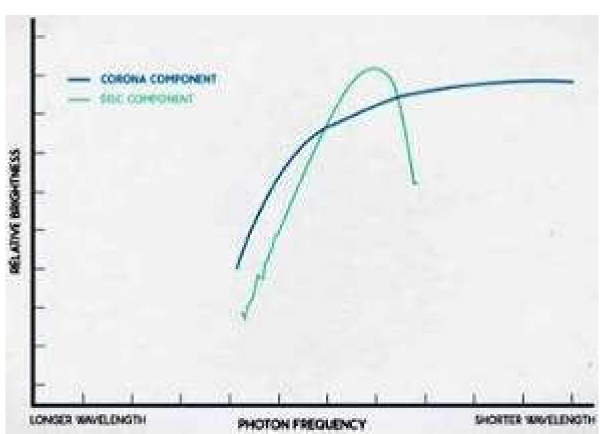
Given that the disc of a supermassive black hole peaks in the UV, you might be surprised to learn that there are a few observations of supermassive black holes made with UV-telescopes. Most supermassive black holes are in galaxies that are moving away from us as the Universe expands. Therefore, the UV-photons that are emitted from the discs are significantly red-shifted, and can be observed in optical or even near-IR parts of the spectrum.

6 Staring Into The Hot Mess

In exploring the X-ray spectrum of black hole, or X-ray binaries such as Cygnus X-1, we noted that there are two major spectral components. The first of these features is related to the disk spectrum of X-ray binaries. Here, we will explore the second major component.



Astronomers have found that the best explanation for this component is a diffuse region of gas that emits fire inverse Compton scattering. This region is often labeled the corona, but it is also sometimes called the hot inner flow.



The component of the spectrum stretches out over a large fraction of the X-ray band slowly increasing in brightness as it extends to higher photon frequencies, or shorter and shorter wavelengths, before turning over and dropping off.

Astronomers think that the emission we observe from this region is fed by the disk. Corona photons are thought to originate from the accretion disc. This means that when photons escape the disk in the direction of the corona, they can interact with the electrons in the corona via inverse Compton scattering and gain energy while moving through the corona. This increase in photon energy can be either small or large. This means that the photons escaping the corona can have a wide range of energies, which results in the long slowly increasing slope observed in a spectrum. We should also note that the electrons in the corona are slowed down slightly as they give up energy to the passing photons.

The coronal spectrum component of the black hole spectrum is clearly visible in the X-ray band for X-ray binaries.

Will this still be the case if the black hole was larger?

We saw earlier that the disk component of the spectrum is shifted to UV-wavelengths for a supermassive black hole.

Is the same true for the coronal component?

The photons from the inner disk feed the corona where they gain energy via inverse Compton scattering. Therefore, the temperature or wavelength of the inner disk photons will influence the temperature in wavelength we observe in the coronal component of the spectrum. Just as the temperature of the disk can be tied to the mass of the black hole, the corona can also be influenced by the mass of the black hole.

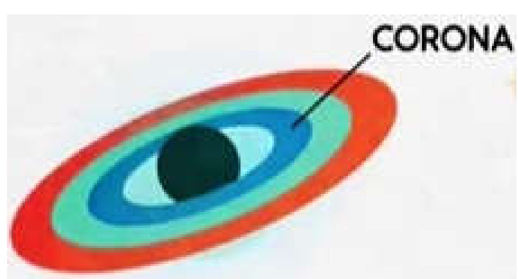
For supermassive black holes, the disk emission is seen to peak in the UV. As such, the coronal component is shifted to longer X-ray wavelengths. However, if the supermassive black hole resides in a galaxy that is moving away from us, the coronal emission will be red-shifted into the optical and UV wave bands.

Now that we know what the emission from the corona looks like, what can this tell us about the structure around the black hole?

6.1 Lamppost Model

There are a couple of different theories for the location of the corona. The first of these is the lamppost model, which suggests that the corona is a cloud of gas that sits at a certain height above and below the accretion disk as if it were suspended on a pole or lamppost.

6.2 Sandwich Model



The second is more of a sandwich model in which the corona and the hot inner flow extend out above and below the accretion disk as well as towards the black hole. In this case, the disk and corona are in contact with one another.

Given the current data that is available from black holes, we know what interactions are happening within the corona.

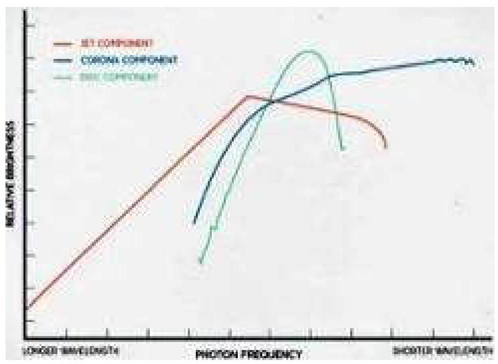
Do we have a lamppost hanging out above the black hole accretion disk, or are we wrapped up in bagels?

As yet, this is still unclear; astronomers are still working to answer this question.

7 Beam Me Up!

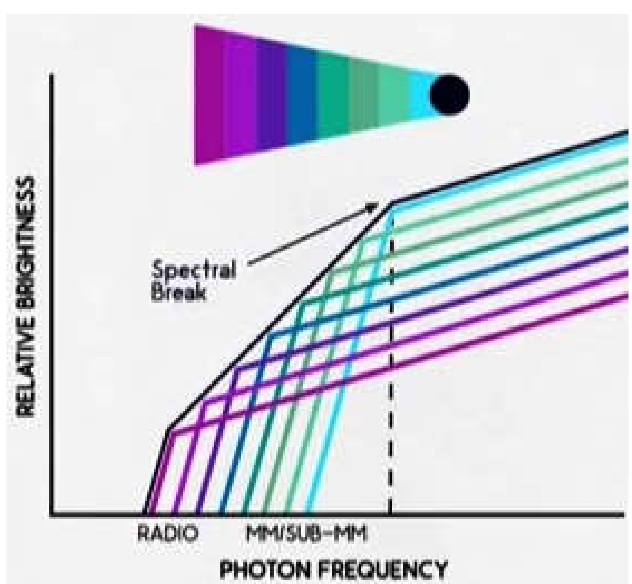
7.1 Jets

Although structures like jets emit in the X-ray region of the spectrum, the X-ray band is dominated by the disc and corona, therefore, X-ray jet emission can be hard to detect in the region directly surrounding the black hole. Jet emission is more commonly associated with radio wavelengths. In this lesson, we will take a look at the spectrum of a black hole, see why this may be the case, and explore the mechanism that creates this emission, discovering what this can tell us about black hole systems.



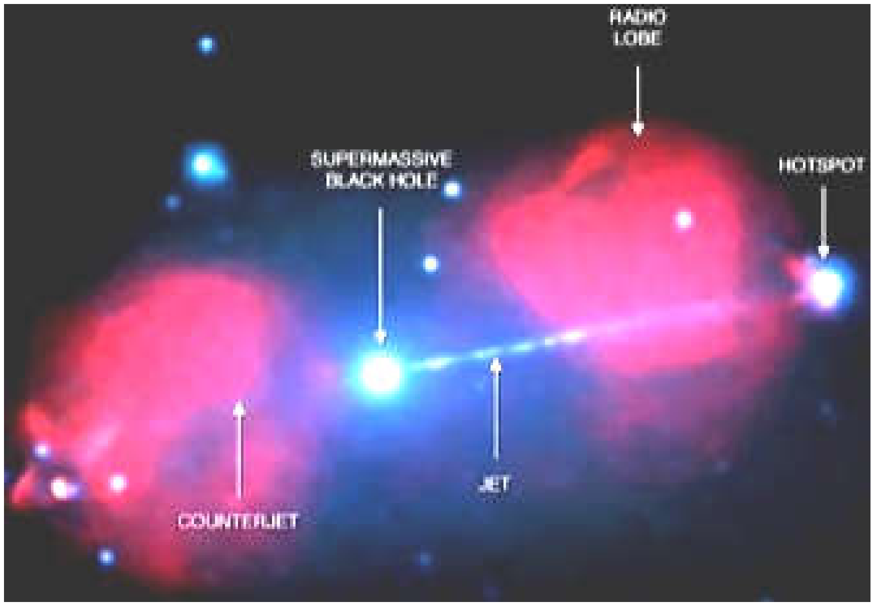
If we return to the plot we have been examining during this module, we can see the addition of this new radio component. From right to left, this new component begins in the same region of the plot as the spectrum of the disc and the corona. The overlap in this region of the spectrum is due to all three components emitting a portion of their energy in the X-ray band. The new radio component then extends to longer wavelengths, or lower photon frequencies, peaking and then tailing off into radio frequencies.

The jet of the black hole is responsible for this new component of the spectrum. Jets are powered by synchrotron radiations, energizing photons through interactions with electrons that are trapped in circular orbits around the magnetic field within the jet. While we do not fully understand the mechanism that is used to launch the jet, astronomers suggest that the magnetic fields within the jet can be thought of as a tangled mess of spaghetti that has been stretched out in one direction. This stretched out spaghetti causes the jet to transfer energy and angular momentum into the surrounding area. Particles energized within the jet can extend out to incredibly large distances.



Similar to the multi-colored disc model, accurate descriptions of jets require us to consider smaller sizes, in order to account for the different energies supplied by the synchrotron emission. If the jet is cut up into narrow disks along its length, like slicing up a banana into small circular pieces. We can plot the spectrum of synchrotron emission from each of these disks. As we move away from the central black hole, the number of particles decreases, along with the strength of the magnetic field. By adding the contribution from each disc of the jet, we can recreate the spectrum of the jet.

7.1.1 Continuous Jet



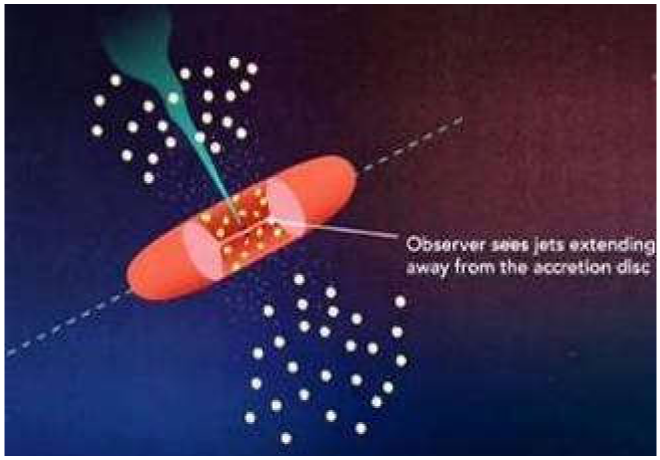
One mystery astronomers are trying to solve is why there appears to be two types of jets around black holes. The first type of jet is a continuous jet, and, just like water spouting from the nozzle of a hose, the continuous jet is a continuous stream of particles, constantly flowing outward along the path of the jet.

7.1.2 Non-Continuous Jet

The second type of jet has multiple names, but it is seen as clumps of particles being emitted out of the jet. Scientists call these clumps, burps, bullets, or ejecta. Just like the continuous jet, jet ejecta provide a route for the spread of energy and angular momentum into the area surrounding a black hole. As a result, jets can sometimes be a mechanism to feed back energy into the region surrounding the black hole system.

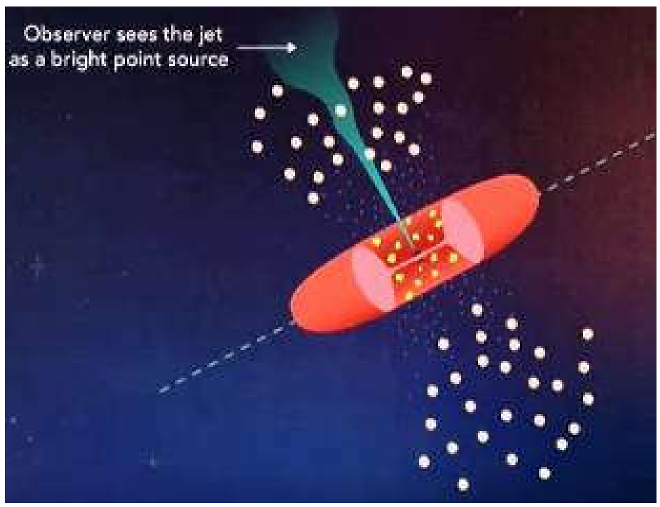
In the last lessons, we have not yet considered how the orientation of the black hole system affects our observations. Since the jets tend to align with the spin axis of the black hole, the direction of their spin determines which way the jets point, and how much light escapes.

7.1.3 Perpendicular Emission



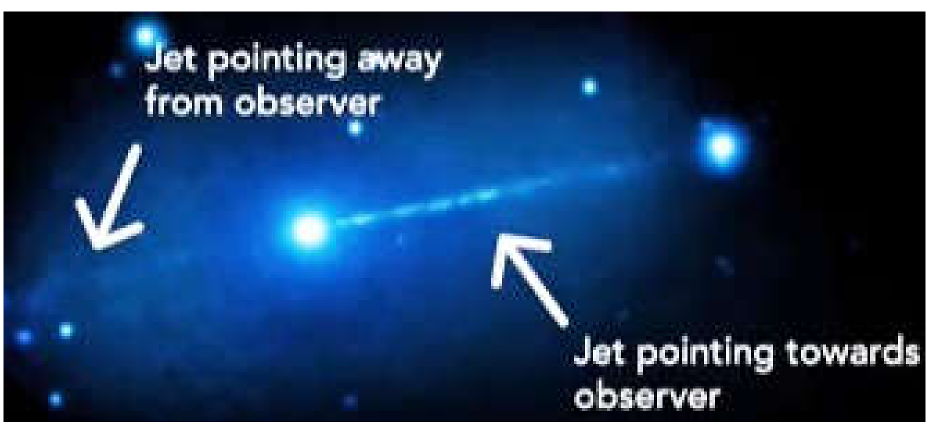
If we are viewing a black hole system with the accretion disc from this side, the jets appeared to extend perpendicular to the center of the disc.

7.1.4 Beamed Emission

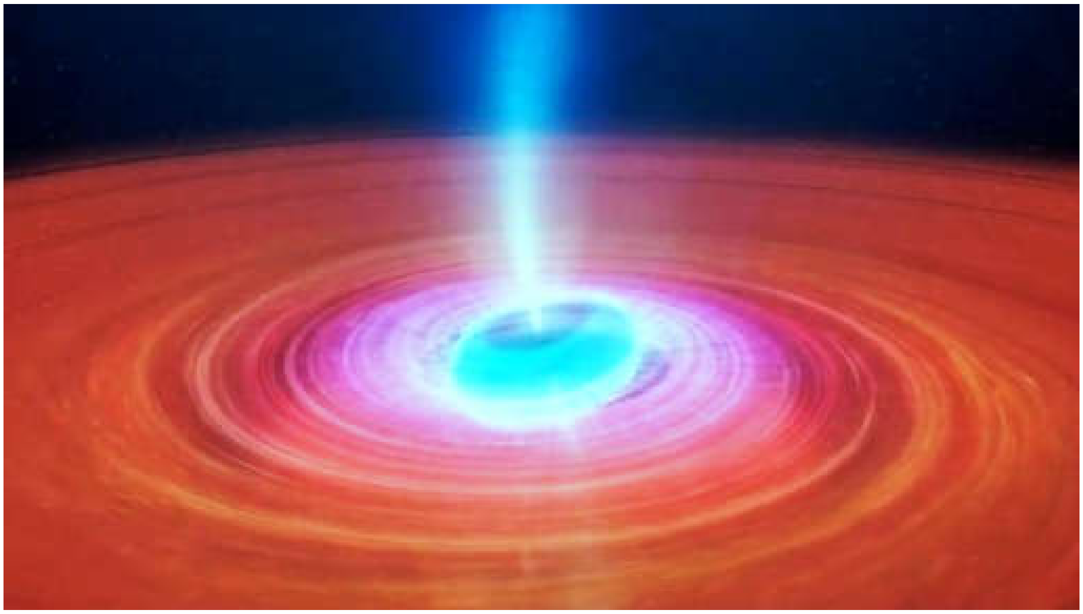


On the other hand, if we see the accretion disc from the top-down perspective, the jet is directly pointing at us, and appears to be much brighter. This is because the emission is beamed towards us, increasing the energy of the photons we receive.

7.1.5 Intermediate Angle



If the system is at an intermediate angle, we will see a blueshift in the jet pointed towards us, while the jet angled away from us will be redshifted. We will also see that the jet angled in our direction is brighter than its counterpart is. We should note that this difference in brightness and color is due to the beaming effect. It does not mean that one jet is actually more powerful than the other is, or that they are emitting different wavelengths.



If the jet is offset from the spin axis of the black hole, then we may be able to detect a wobble from the jet. This has been recently seen in observations of the black hole binary known as V404 Cyg. A research team, including professors here at the University of Alberta, has been looking at V404 Cyg, to investigate its jet in more detail.

8 Summary

In this module, we learned how astronomers observed black holes using the electromagnetic spectrum. To explore the nature of black hole systems, we require telescopes that allow us to image the black hole's features in a large range of wavelengths from radio to X-ray and beyond. Astronomers use the technique of spectroscopy to spread the light into an extended rainbow, therefore, that we can understand the radiative processes, like synchrotron radiation and Compton scattering, that take place near the black hole. Spectroscopy allows us to see the fantastic sites such as the jets, corona, and accretion disk around a black hole.

Now that we know the components of a black hole spectrum, why do astronomers continue to look at black holes?

The reason we keep looking is that the spectrum of black holes, like the black hole systems themselves, change over time. In the next lessons, we will take this a step further to examine what changes we observe. We will explore black holes that are on a strict diet as well as those that are extreme eaters, and see how their meals change and how they appear to us.

Our Eyes in the Sky

1 Turn To Face The Strange

Astronomers have been looking at black holes since 1963.

We have learned a lot, but if we know all of this, why do astronomers keep asking for more money to build better telescopes? Why keep looking at black holes? What can we learn more about the systems that we do not already know? After more than 50 years, why have astronomers not cracked the mysteries of black holes?

Black hole binaries have helped us navigate our way through much of this course. We have picked them apart, and put them back together again, discovering what they contain, and how they work in the process. The black holes that we have explored have a companion star that is sending mass towards the black hole. The material that is stripped from the star passes through a disk and a corona to get the black hole. Unless it is thrown out via jet.

Looking at black hole binaries with visible light alone, can be quite limiting. Therefore, we expanded our view to include radio, IR, UV, and X-ray telescopes. These observations help astronomers learn about the underlying physics of each of the components of the binary system.

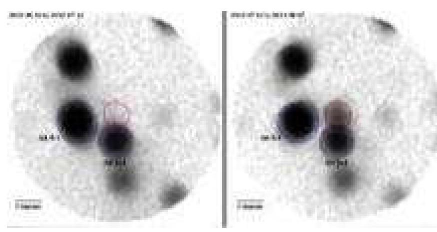
The reason for continued observations and studies is that a black holes properties change over time. The brightness of a black hole depends on what the black hole is eating, and whether it is actively feeding at all.

If the black hole is eating, is it leisurely afternoon tea or a crazy pie eating competition?

The rate at which black holes consume food can dramatically affect what we see through our multi-wavelength spectacles.

2 To Feed Or Not To Feed

To feed or not to feed? That is the question. When is a black hole eating, and when is it taking a rest?



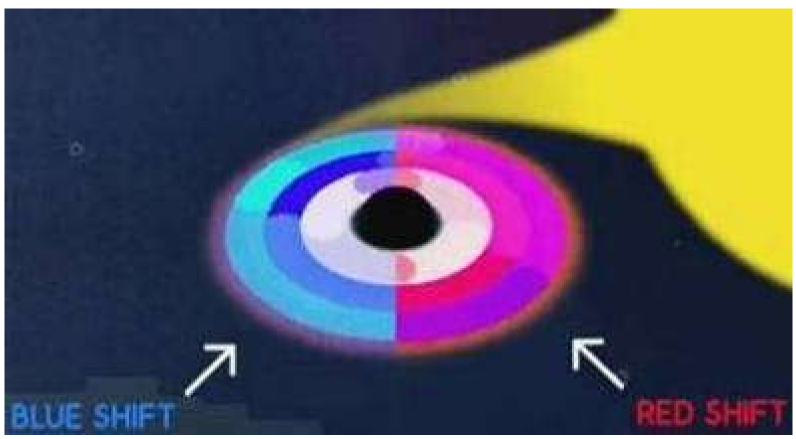
The black hole candidates that we observe in the sky are not always dark, and they do not always have bright accretion disks either. Black holes change in brightness and emission wavelengths depending on how they are eating.

A better question to ask might be, how does a black hole actually reach its food?

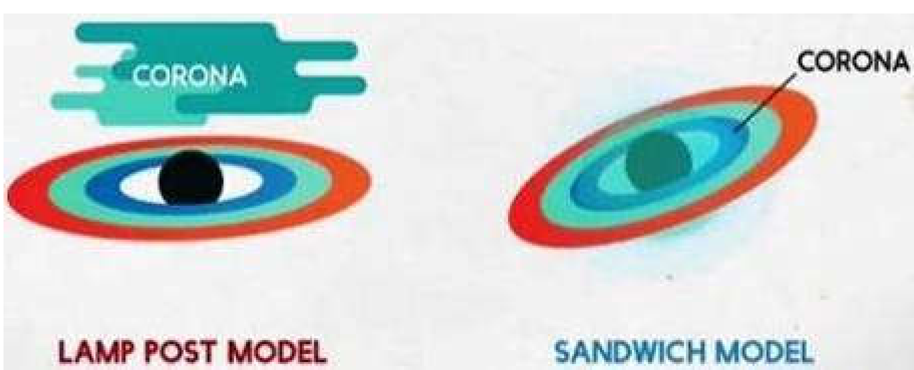
We know that if anything strays too close, the black hole will gobble it up. Almost by definition, that is what black holes are.

If a star, a cloud of gas, salmon, spacecraft, or an astronaut venture too close to a black hole, they will be pulled inwards, as well, into the accretion disk. The emissions from the accretion of material onto the black hole cause the black hole's accretion disk to become visible across the electromagnetic spectrum, from long radio wavelengths to short X-rays and γ-rays.

It is only when a black hole is feeding that astronomers are able to investigate the type of food that it is feasting on. It could be sipping on a star, nibbling on a nebula, digesting dust, or even slurping up spaghettified space travelers. An actively accreting black hole can provide astronomers with the opportunity to test and gain a greater understanding of the underlying physics governing the processes, which feed the black hole including opportunities to put general relativity to the test in the strongest gravitational environments known to science.



One of the effects astronomers measure is the Doppler shift that occur due to the rotation of the accretion disk. If we look at a disk up close, we can see that one side is moving towards us, while the other side is moving away. As the disk spins, the light emitted from the side moving towards us is blueshifted, because the light wavelength is compressed, while the photons we receive from the side moving away from us are redshifted. Their wavelengths are elongated.



Observing accreting black holes is a major test in determining the veracity of competing scientific models. The corona, for example, is thought to be described by the lamppost model or the sandwich model. My stomach already likes the sound of the sandwich model better.

A black hole's jet also comes in two flavors, and observations can help us understand the relationship between them. First, we need to learn about black holes that are not eating.

A hungry black hole drifts through space with nothing to eat. Since it is not emitting light, black holes that do not have enough food are nearly impossible to detect, but scientists are building better tools all the time. However, the reason these drifting dark spheres are interesting, is that there are a large number of them. Mathematically speaking, there are many more black holes out there than the ones we see. Simply because black holes are difficult to see. On the British TV-series, 'Red Dwarf,' the computer Holly says, 'The thing about a black hole, its main distinguishing feature, is it is black! In addition, the thing about space, and your basic space color is its black.

How are you supposed to see them?'

Well, it is hard but not impossible to find these isolated black holes. Since black holes have a strong gravitational field, they create large curvature in space-time around them. Curved regions in space-time can act as lenses, which can reveal a black hole due to the warped background images of distant stars and galaxies. In fact, a hungry black hole gives astronomers the best evidence for the foods they dine on.

For example, if a black hole were in a wide binary system far from its companion star, we would distinguish between the star's light and the light produced by the accretion disk. A wide binary system like this can tell us a lot about the black hole. Its mass and, therefore, its size, just to give you an example. However, if the black hole is close enough to its companion, the material it draws inward can get so hot and so bright that they become brighter than the parent star itself. The light being emitted from the star becomes difficult to distinguish from the light from the disk. In a sense, a binary system like this might look to astronomers the way a firefly dancing above a campfire might like to you across a dark field.

3 Classifying Black Hole Binaries By Their Food Source

Stellar-mass black holes are most easily identified when they are accompanied by a companion. The gravitational effect of a black hole on its companion star can help give us a location where the black hole might be hiding. If the black hole is actively feeding on the companion star, we will be able to see this clearly in the X-ray portion of the spectrum.

3.1 X-Ray Binaries

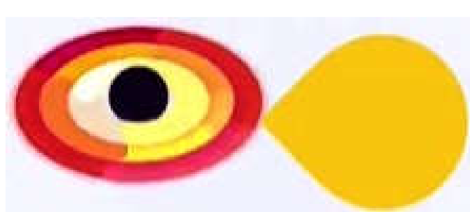
In fact, because the systems are so bright in X-rays, they are often referred to as X-ray binaries. We should note, however, that this term refers to systems containing a star and a compact object. As we are aware, compact objects can be either neutron stars or black holes. As such, it is important that when we observe these systems we try to find the mass of the compact object. If the mass of the compact object is more than three solar masses, it must be a black hole. If it is lighter than that, it is likely a neutron star. In some cases though, it can be very hard to tell the mass of the compact object. When astronomers are unsure of the characteristics of systems like this, they list them as a black hole candidate.

There are two types of X-ray binaries: high-mass X-ray binaries and low-mass X-ray binaries. However, this classification is not based on the mass of the compact object. It may seem strange to you at first, but X-ray binaries are classified by the mass of the companion star, not the compact object. The companion stars in low-mass X-ray binaries have masses that are the mass of the Sun, or smaller. High-mass X-ray binaries have companion stars that are at least 10 times more massive than the Sun.

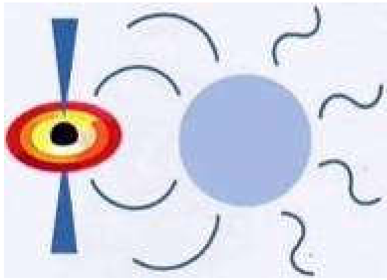
Any time astronomers come up with a classification like this, you will find that some objects do not quite fit. Therefore, we also have an in-between group that is sometimes called intermediate-mass X-ray binaries, but their properties are usually pretty similar to the low-mass X-ray binary group.

Why would astronomers choose to classify binary systems based on the type of companion star, rather than the type of compact object?

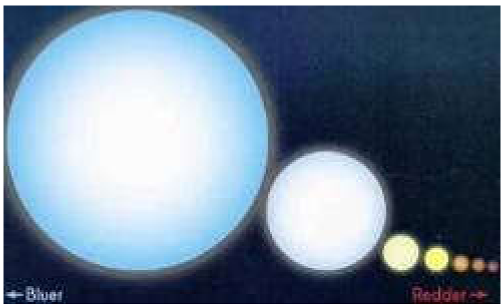
3.1.1 High-Mass And Low-Mass Binaries



The reason for this classification is that the properties of the system depend more on the type of the donor star than the type of the compact object. What this means is that observations of these systems vary more dramatically if you compare high-mass enormous X-ray binaries than if you were to compare stellar-mass black holes and neutron stars that are both feeding on, say, a low-mass star. When their companion is a low-mass star, such as in a low-mass X-ray binary, the gas from the companion star flows to the black hole via Roche lobe overflow that we studied in an earlier lesson.



In addition, recall high-mass stars tend to have larger outflows of material in the form of powerful stellar winds. In high-mass X-ray binaries, the mass loss through wind ends up being accreted onto the black hole. This is called wind fed accretion. However, we should note that high-mass stars could also feed black holes via Roche lobe overflow.

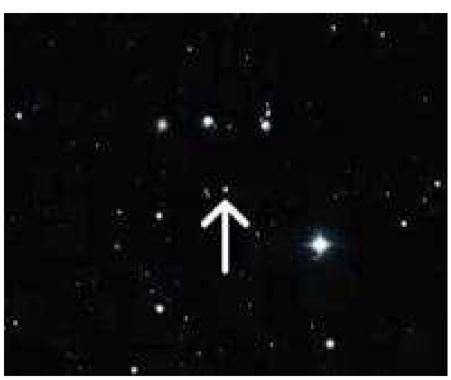


Typically, low-mass companions are small in size, while high-mass companions are large. Small stars can orbit closer to the black hole than large stars can. Kepler's laws of motion tells us that stars with small orbital separations orbit with faster speeds and take shorter amount of time to orbit. Lowest X-ray binaries typically have short orbital periods that can range from less than an hour to many hours.

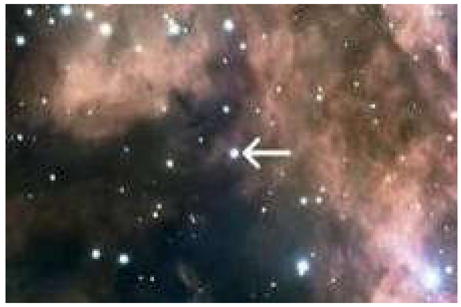
Meanwhile, the larger companions in high-mass X-ray binaries orbit further away from the center of mass of the system and can take a few days to complete one orbit. This means that the feeding or mass transfer mechanism, and therefore, the rate of mass transfer along with the orbital period can be greatly impacted by the type of companion star.

Stars are usually classified by observing their color in visible light, since this is the portion of the spectrum where they are usually the brightest. We have already learned that accretion disks around black holes will also emit some visible light. This means that, if we want to view the companion star of the black hole, we will have to wait until a black hole was finished eating a major meal, therefore, that the disk is not emitting light, which would otherwise pollute our image.

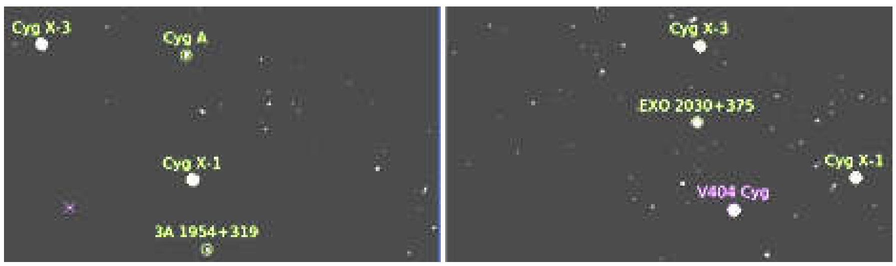
When astronomers want to classify a star, they look at it using different filters to determine the star's properties. Low-mass stars with masses less than the Sun's mass are dim, and have colors that range from yellow to orange to red. High-mass stars are bright and blue in color.



Since low-mass stars are dim, they can be difficult to detect. Therefore, sometimes we have trouble detecting the companion in a low-mass X-ray binary system, and the binary is classified based on its X-ray emission instead.



The companion stars in high-mass X-ray binary systems are usually easier to see since they are so bright, meaning that, in many cases, we can also obtain a detailed spectrum of the star. Therefore, it is not at all surprising that the first confirmed black hole, Cygnus X-1 has a bright blue high-mass companion star. However, accretion disks can also look very blue, bluer in fact than hot blue stars. This means that when the disk is bright, it can be incredibly hard to work out what kind of star is feeding the compact object.



X-ray images of black holes are not quite as impressive to look at as some of the other types of images we have seen in this course. They can be fairly featureless with just a series of dots scattered in a black section of the sky, except, of course, when they are suddenly change. The left-hand image shows an X-ray image of the sky near our old friend, Cygnus X-1. In the left image, taken before June 2015, we see full bright X-ray point sources. Cygnus X-1 is the brightest X-ray source in Cygnus, and a high-mass X-ray binary. Cygnus X-3 was the third X-ray source discovered in Cygnus, and is a low-mass X-ray binary. At this moment, it is unknown whether there is a neutron star or a black hole in Cygnus X-3. 3A 1954+319 is also a low-mass X-ray binary, most-likely harboring a neutron star. Cygnus A is a supermassive black hole, but it looks dim, because it is in a galaxy far, far away, while the other sources are in our own galaxy. V404 Cyg suddenly became as bright as Cygnus X-1 and Cygnus X-2 in June 2015.

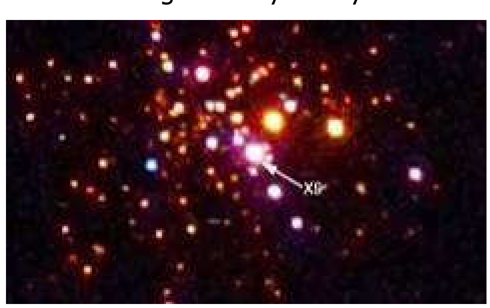
V404 Cyg is close to 8,000 ly away from us. The companion is a type K star, which means that it is orange in color, and has a mass that is just 40 % of our Sun's mass. The black hole has a mass that is seven times our Sun's mass. Therefore, there is no danger that this could be a neutron star masquerading as a black hole.

At this point, please watch Astro-101_019.mp4

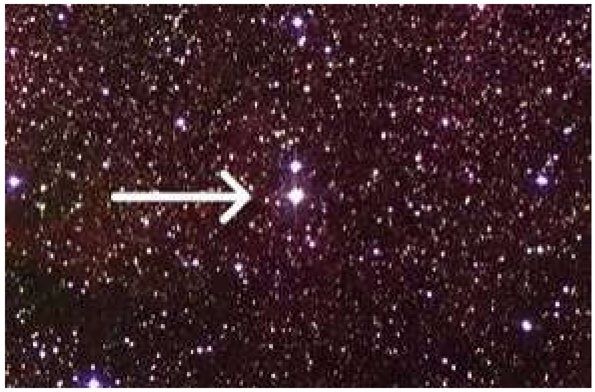
Video 19 : X-ray emission from V404 Cyg's accretion disc

3.2 Dynamical Formation

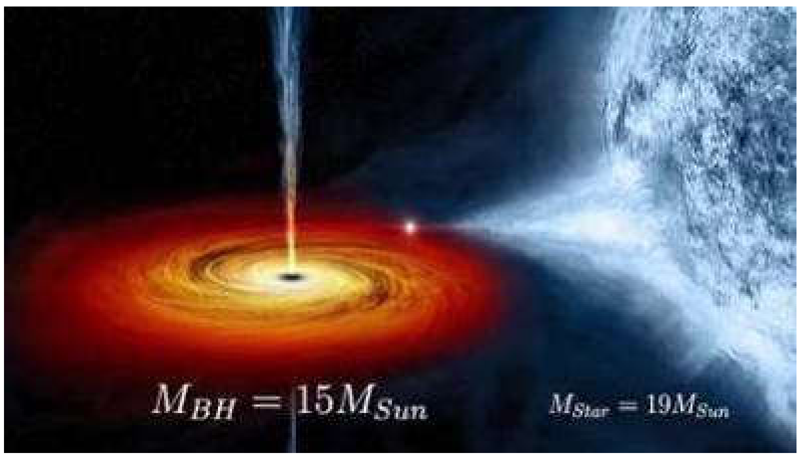
Another example of a low-mass X-ray binary is the X-ray source X9 in the globular cluster named 47 Tuc. A globular cluster is a dense star cluster that can have many millions of stars. Since the stars are closer to each other than in part of the galaxy where we live, the stars can easily hook up with other stars to form binary systems through dynamical formation. Therefore, if you were to choose randomly a globular cluster to look at with an X-ray telescope, you would have a good chance of finding an X-ray binary.



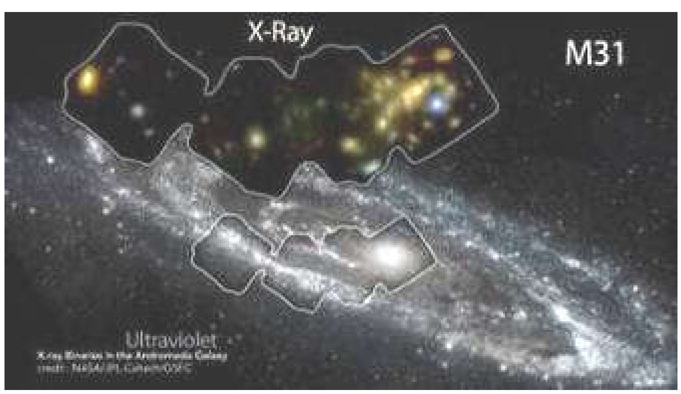
The X-ray binary X9 is still classified as a black hole candidate, since its mass has not yet been measured, but the orbital period is very small, only 25 min, and the companion star is most likely a white dwarf.



The companion star to the black hole Cygnus X-1 is easily seen as the bright star in the very center of this visible light image of the constellation Cygnus. Since this is a visible light image, we cannot see the accretion disk of the black hole. The red light is coming from glowing H-gas in a nearby star-forming region. Cygnus X-1's companion star is named HDE 226868, but for obvious reasons, we normally call it Cygnus X-1's companion star.



The companion is a type O supergiant that has a larger mass than the black hole. The companion star's mass is 19 times larger than the Sun, while the black hole's mass is 15 times the Sun's mass. The two objects orbit their common center of mass, which is closer to the companion, once every 5.6 days.



Both high-mass and low-mass X-ray binaries are spotted scattered throughout galaxies. They are relatively easy to spot, because the black holes have their dinner sitting right there next to them in the binary system.

What happens when we switch up to other size scales? What are the alternative diets for supermassive black holes?

4 The Alternative Diets For Supermassive Black Holes

Much of our discussion around the feeding of black holes has revolved around stars, the snack of choice for stellar-mass black holes.

Since stellar-mass black holes make up the majority of binary pairs we associate with stellar companions, what do you think a supermassive black hole likes to snack on?

4.1 Tidal Disruption Event

Well, if you were thinking surely they also eat stars, you would be correct, but they are also voracious consumers of the gas and dust that happened to fall into close. Some of the most spectacular phenomenon theorized to occur in the environment around a supermassive black hole are called tidal disruption events. These feeding frenzies are so violent that the stars being consumed are completely torn apart.

During a tidal disruption event, stars passing close to a supermassive black hole are disrupted by the strong tidal forces of the black hole's gravitational field. The tidal forces deform the star into a long string of hot glowing gas, just like this artist's impression of what a disrupted star might look like.

Astronomers can detect these tidal disruption events as a sudden increase in the brightness of light around the black hole. However, direct imaging of these disruptions is not yet possible, which is why we only show an artist drawing here. The gas from a destroyed star then accretes onto the disk of the supermassive black hole feeding its insatiable appetite.

This effect was used in the 'Doctor Who' episode, 'The Impossible Planet,' when the Scarlet system, which was home to the Baluchi, was drawn out into a red cloud before being accreted onto a black hole.

Supermassive black holes can feed on stars, but the gas that the black holes devour does not have to come from a disrupted star.

Are there other options? What is about clouds of dust and gas?

Illustration 120 : Cold gas cloud

The centers of galaxies can be pretty messy after all. Astronomers are puzzled by the sheer size of supermassive black holes. The mass of their interiors came from somewhere, and until recently, scientists thought that supermassive black holes feed on a steady diet of hot ionized gas from the halo of the galaxy. Similarly, supermassive black holes can feed on cold molecular gas clouds, sometimes the remnants of ancient supernova explosions. In this case, the food is more like a soup with lumpy noodles and vegetables in it.

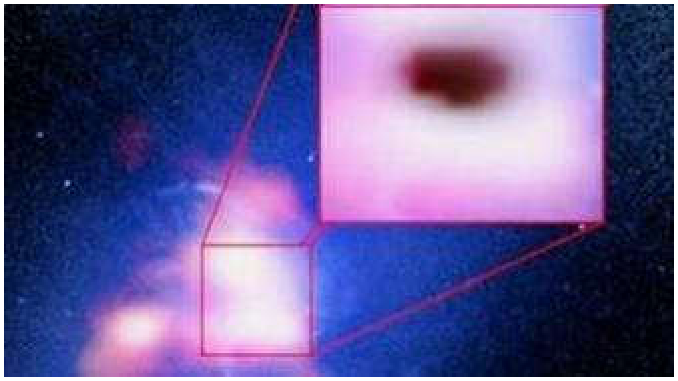


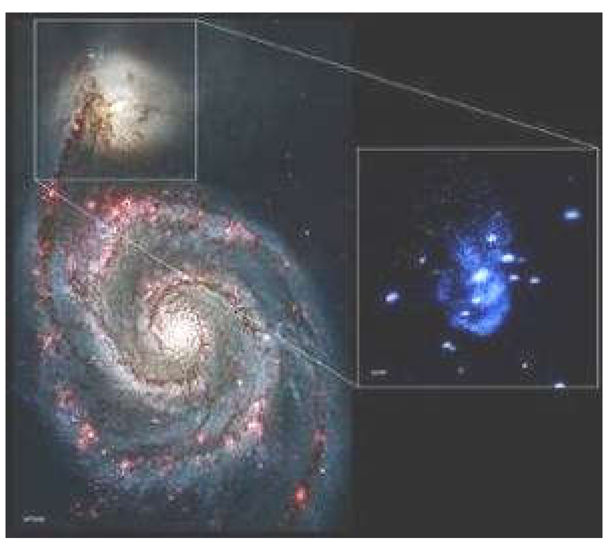
Illustration 121 : Center of Abell 2597

In this image, the supermassive black hole is hidden away in the center of the galaxy in the cluster Abell 2597, which is shown as blue light in this image. The red blobs show the location of cold clouds of molecular CO-gas.

When a lumpy CO-chunk is consumed by a black hole, it temporarily blocks the light emitted from the accretion disk and jets like the black blob in the inset of this image.

Supermassive black holes are not the most eloquent of dinner guests either. Not only do they demand more, they do not care whether you serve them a delicious apple pie made from scratch, or a pile of rocks. While they do clean up after themselves, we can all agree that they need to work on their manners. No one is going to sit at a table with a supermassive black hole.

We have also learned that the jets of a black hole are hot gases being accelerated into interstellar space; this is like a black hole burping. While gas flows inwards towards the black hole, the material and energy can be thrown out in the form of powerful relativistic jets. On closer inspection, astronomers have also found that supermassive black holes can also eject gas from the region even closer to the event horizon.



Here, we see the Whirlpool galaxy, a beautiful example of two colliding galaxies. The smaller galaxy visible in the inset has a bright X-ray source visible in blue, which indicates the presence of a supermassive black hole. The blue arcs and bands are hot glowing gas being ejected from the region around the black hole; this is evidence of black holes burping.

We have a supermassive black hole at the center of our own galaxy, Sagittarius A*. I wonder what its favorite foods are.

5 The Special Case Of SGR A*

Illustration 122 : Milky Way galaxy seen from Earth

Our Sun resides in a little corner of the Universe known as the Milky Way galaxy. So named because of the milky path that leads across our night sky. The milky path that we see is made up of about 100 billion stars, each in a lazy orbit around the center of the galaxy that takes around 200 million years.

An observer on Earth, looking towards the center of the galaxy, would see the constellations of the Scorpios, the scorpion, and Sagittarius, the archer. I think Sagittarius looks more like a teapot. Sagittarius is where our central supermassive black hole gets its name, Sagittarius A*, which is sometimes shortened to SGR A* as nickname. This constellation is easiest to observe in July and August, when it is visible in the evening sky. Looking at the constellation of Sagittarius, we see that the bulge of the Milky Way is located at the westernmost end of the teapot.

Illustration 123 : Milky Way center (Enhanced)

Since Earth hangs out in one of the outermost arms of the Milky Way galaxy, tilted with respect to the plane of the galaxy, it is actually easier for observers in the southern hemisphere to enjoy the view of the galactic bulge. Notice that the more we zoom into the center of the galaxy, the more crowded the stellar environment becomes.

Even though we call Sagittarius A* a supermassive black hole, it is a lightweight contender in the supermassive category. One of the reasons SGR A* is not bigger, is that it is not presently eating very much at all. It sits in a region with many stars, but none of them has strayed within gravitational reach for SGR A* to grab.

What is so special about Sagittarius A*?

Well, it is probably the only supermassive black hole within about 2,500,000 ly. The next nearest known supermassive black hole is at the core of the Andromeda galaxy. Due to the proximity to Earth, SGR A* is the most studied supermassive black hole, and we are fortunate that it is not currently eating. This gives us an excellent opportunity to see the environment around it without being blinded by the glare from the accretion disc.

If SGR A* is not currently feeding, how do we even know it is there?

While scientists using ESO's very large telescope, have actually image the core of the galaxy, and revealed the motion of the stars and dust clouds surrounding the central black hole. From 2000 to 2011, this video shows the stars orbiting Sagittarius A*. Which reveal to astronomers just how massive the black hole is.

Illustration 124 : Simulation of gas cloud approaching SGR A*

In fact, one of the objects, called G2, is not a star at all, but a cloud of molecular dust. Researchers predicted that G2 would be captured by the gravity of the supermassive black hole, with a collision around 2014. They predicted it would be consumed by Sagittarius A*, causing it to light up in the X-ray spectrum. However, when G2 passed the central object not much happened. It is still a mystery why G2 was not eaten by Sagittarius A*.

6 The Hermits Of The Black Hole Family

Until now, we have only discussed black holes that either are in a binary star system, or located at the center of a galaxy. Surely, those are the only ways to find black holes. Indeed, scientists think that there are isolated black holes lurking within our galaxy.

How do we detect them?

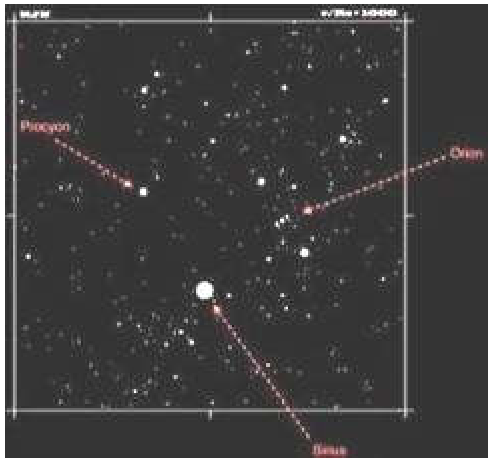
6.1 Interstellar Medium

We need to remember the presence of gas between stars called the interstellar medium. If an isolated black hole travels through a gas cloud, we would expect to see some of the gas to accrete onto the black hole. The accreting gas should emit X-rays, which could potentially be detected. Although, astronomers detect many X-rays emitted from gas clouds, conclusive evidence for isolated black holes using this method has not been detected.

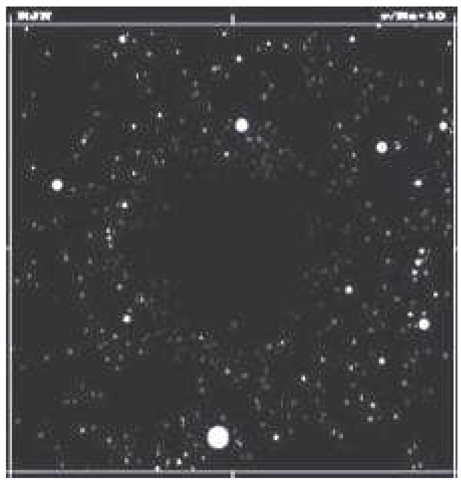
If there is no light being generated by an isolated black hole, is it still possible to detect them?

6.2 Gravitational Lensing

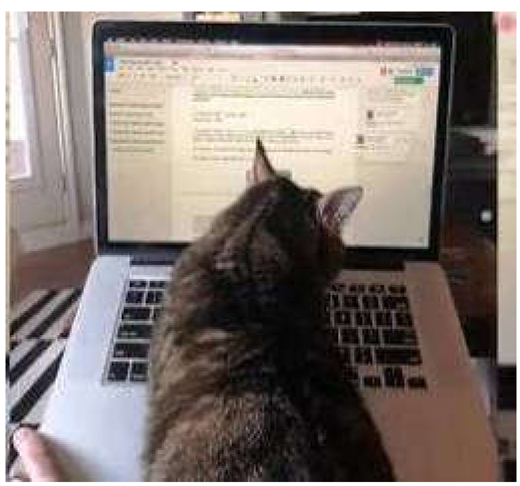
Of course. Black holes change the gravitational field in their local environment. Therefore, light passing by is influenced by the gravitational field. Since black holes can strongly warp space-time, they cause light to travel on curved paths. We see the light from behind the black hole as being worked by gravity. This is called gravitational lensing.



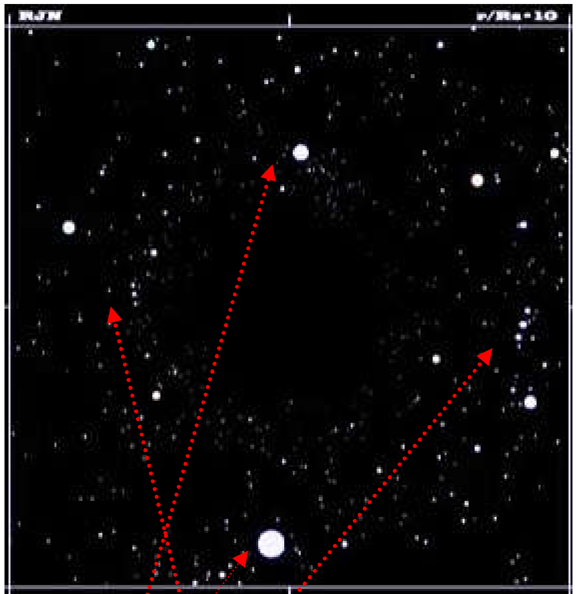
Here is a computer-generated star map showing the constellation of Orion along with the bright stars Procyon and Sirius. Brighter stars are represented by larger circles, and dimmer stars by smaller circles. Light cannot escape if it enters the black hole's event horizon.



Therefore, if a black hole were to get in the way of our view of Orion, we might see something like this computer-generated image, with a dark circular region where we see no stars. The black circle corresponds to the event horizon of the black hole.



The black hole is blocking our view in the same way a cat blocks your view when it decides it is time for attention.



However, if we look carefully at the area around the dark region, it looks as though many more stars have appeared around its outer edge. The strange appearance of these additional stars is an optical illusion. What we are actually seeing are multiple images of the stars that reside in the background. For instance, you should be able to see two images of the group of three belt stars on either side of the black hole. Similarly, you can see two images of the very bright star called Sirius.

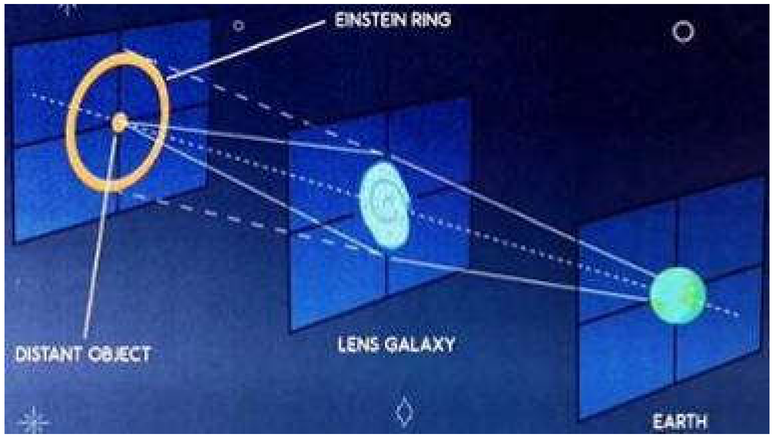
What we would see is more complicated than just a black circle in the sky. Instead, light from the faraway stars curves around the black hole, and arrives in our eyes as though the star is located at many locations. The black hole's gravity distorts the image of the background stars, giving away its presence. In reality, there is no black hole close enough to give us a view like this distorted illustration of Orion, but we can use the concept of gravitational lensing to identify some isolated black holes.

If this lensing effect is difficult to wrap your head around, you probably feel like a photon that has been bent in the space-time around a black hole. Let us have a look at a real-world example of image distortion by your dining room glasses. Stemmed glassware is a simple vessel that can be filled with a liquid. Since an empty glass has curved edges, it bends and warps light just like a lens. When the glass passes in front of an illustration, like this star map, a distorted view of the background becomes visible. Since the curvature of the glass allows multiple images of the same object, we see multiple images of some stars. Depending on where the stars are, they can also be distorted into rings.

When gravity is weak, light travels on paths therefore that we consider it straight. Since gravity can distort space-time, photons are forced to travel along geodesics, which are curved paths that bend around the black hole. To us, the resulting images have multiple views of the same object along with great arcs of refracted lights similar to what we saw in the glasses. For this reason, when the gravity of a massive object curves the path of light, we call the massive object a gravitational lens. A gravitational lens can be a star like our Sun, a galaxy, or a black hole. The more massive, the better.

6.3 Einstein Ring

When the faraway object, the nearby mass, and the Earth have perfect alignment, the image that we see is called an Einstein ring.



This diagram demonstrates the perfect alignment between the Earth and a nearby galaxy at a faraway star. Light from the star can be emitted on paths that go around the galaxy and reach the Earth in many different ways. The light can go over, under, or beside the galaxy. The result is that the light in our telescope from the distant star looks like it comes from a ring in the sky that surrounds the nearby galaxy.

Illustration 125 : Einstein ring

Here is an example of an Einstein ring captured in a photo taken by the Hubble space telescope. The fuzzy orange blob in the center of the illustration is a nearby galaxy. The blue circular halo is a distant galaxy lying behind the orange galaxy. The mass of the nearby orange galaxy warps space-time, and the light from the faraway blue galaxy appears like a ring due to the gravitational lensing effect. The ring is not a perfect circle because the orange galaxy's mass is not located at one point.

6.4 Einstein Cross

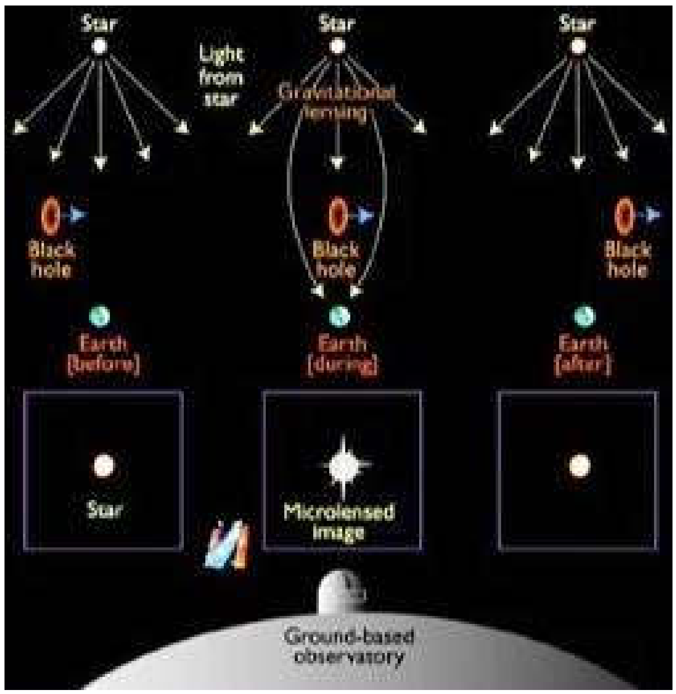
Illustration 126 : Einstein Cross

If the source of light and the lens' mass do not line up perfectly, we see multiple copies of the same faraway galaxy. In this illustration, we see four lights that are all images of the same faraway quasar that is behind the nearby galaxy. The nearby galaxy is the fuzzy light in the center of the four quasars. This is called an Einstein cross, since it resembles a cross.

When astronomers view images of gravitational lensing, they can compute the mass contained in the nearby galaxy. In many cases, the mass calculated from gravitational lensing is larger than the mass infer from looking at the bright stars. This is one method used to show the existence of dark matter in galaxies. Although black holes could be a type of dark matter, most dark matter is not made of black holes.

6.5 Gravitational Micro-Lensing

The size of an Einstein ring is related to the mass of the nearby object. For the images that we have shown, the nearby mass is a galaxy, and galaxies have gigantic masses larger than 100 billion suns. The large mass gives a large deflection, and a bigger looking Einstein ring. If the lens mass is small, where small means similar to the Sun's mass, and the distance is far from us, then the size of the ring will be too small for a telescope to resolve. Instead of seeing a ring, the light from the faraway star will appear brighter. This situation is called gravitational micro-lensing. The mass causing the lensing could be a dim star like a brown dwarf or a black hole.



Astronomers have been monitoring many stars in a nearby galaxy to look for the micro-lensing brightening effect due to an isolated black hole in our galaxy. If the black hole is traveling between the Earth and the faraway stars, then they will appear brighter while the black hole is in front of them. This gives us a view of a star that appears brighter for a short time period.

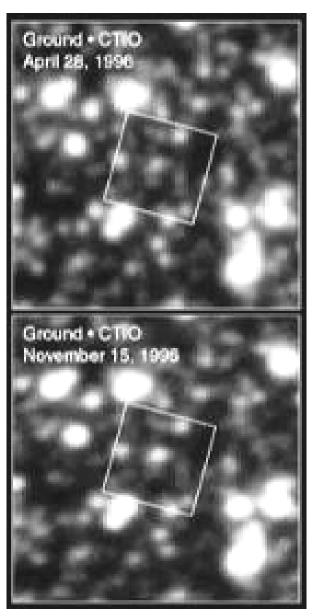


Illustration 127 : Gravitational lensing

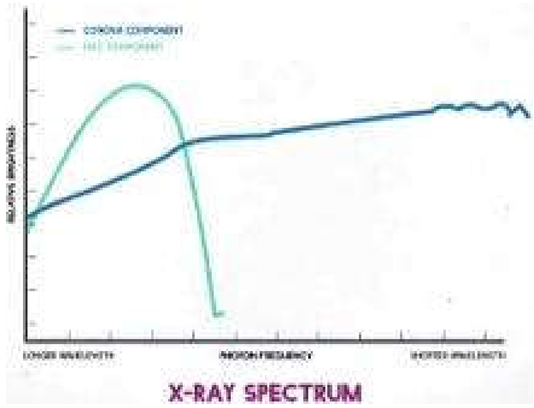
Micro-lensing by black holes is very rare, but it is seen occasionally. This image shows a gravitational lensing event that occurred in 1996. The top panel shows a dim star on April 28, and the bottom panel shows the same star on November 15. The image on November 15 is brighter, and a further analysis shows that the star appears brighter, because a black hole with a mass around ten times larger than the Sun passes by. Only a handful of black holes have been found this way since this is a really rare event.

7 It Is On... Now What?

Black holes will eat whenever there is something for them to grasp in their gravitational clutches. The rate they eat depends on how much material can be captured, which means that, just like people, black holes will eat at different rates, and at different times. Sometimes you are having an off day, you do not really want anything to eat, or you may be fasting. Yet on high days and holidays, you may overindulge, eating much more than normal.

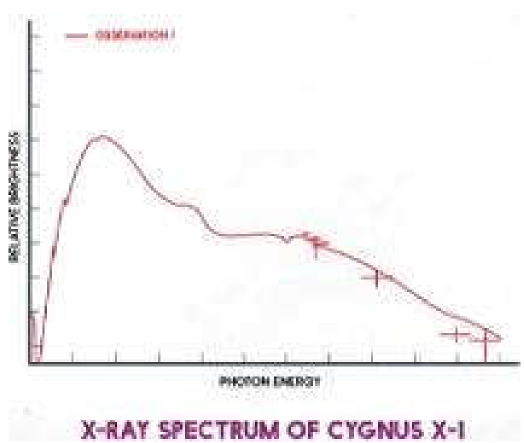
Although black holes do not really choose their food in the same way we do, they can go through cycles of feast, or famine, or anything in between. This change in food intake can result in change in the strength of the different components of the spectrum of the black hole.

What are these changes, and what do they look like?



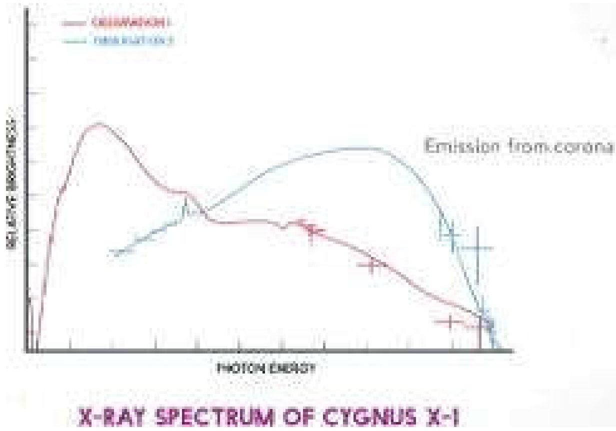
If we take another look at our spectrum of an accreting stellar-mass black hole, we can see the different components about that we have learned. We have an accretion disc, a corona, and a jet. If we zoom in on this plot to take a look at just the X-ray band, we can see the two X-ray components more clearly. Here, we see that the disk is dominating the emission from the black hole while the corona slopes gently upwards as we move to shorter wavelengths.

Now let us look at some real data taken from an old friend Cygnus X-1, and see how this compares. If you recall, Cygnus X-1 is a black hole binary that contains a stellar-mass black hole weighing in at about 15 times the mass of our Sun, and a hot blue companion star.



If we look at the X-ray spectrum of this source, we can see a large bump at lower X-ray energies, which is explained by the thermal emission from the accretion disk. The boom's long tail as it is sometimes referred to extend to higher photon frequencies, or shorter wavelengths. The spectrum looks pretty similar to what we were expecting to see.

What have we seen during a different observation of Cygnus X-1?



Something quite different. The blue line has a steeper incline increasing towards higher energies and seems to peak in the same area as the plot that we would expect to see the corona.

What is happening here?

The truth is scientists have not collected enough information to know for sure. This is the type of change that drives astronomers to continue investigating these sources and for them to ask the questions about what could be causing these changes.

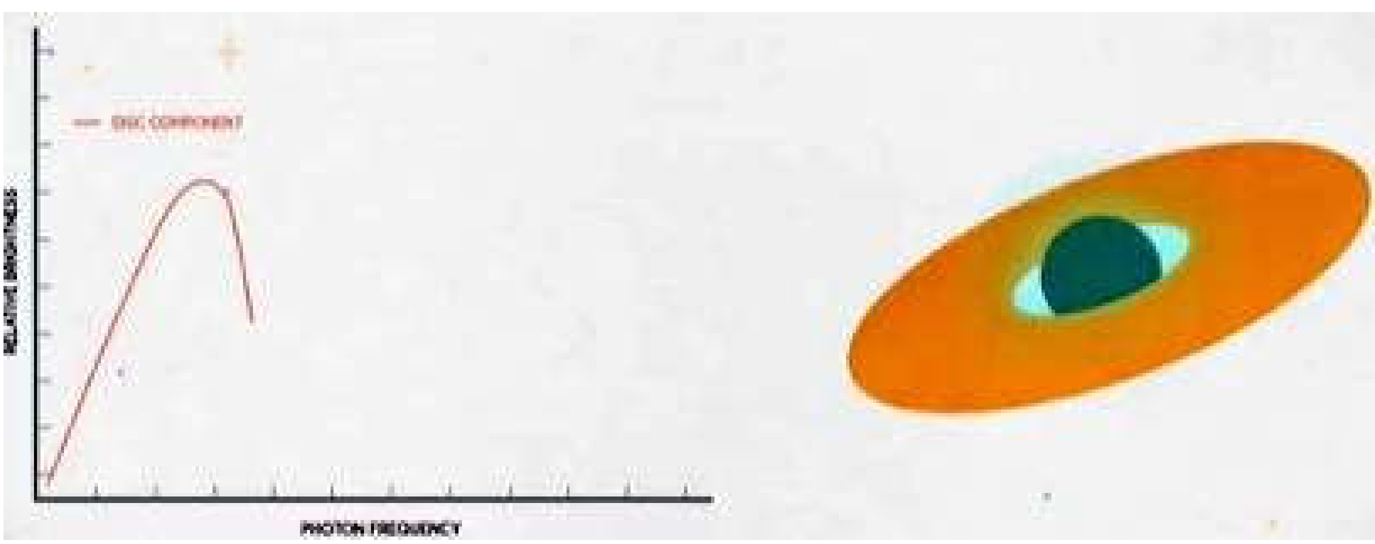
Our view of black holes changes over time. Sometimes we can get more emission from the disk, while at other times we can receive more photons from the corona.

What physical mechanism could be driving this?

One of the leading theories is that the change for food available to a black hole changes the portion sizes of each component. As the amount of food from say, a companion star change, the serving size of a disk could decrease while the corona increases. When we look back at the image we built up during former lessons, we saw the disk extending towards the black hole with the corona that could be explained by either the lamppost model or the sandwich model, with light coming from both the corona and the disk as material moves in towards the black hole.

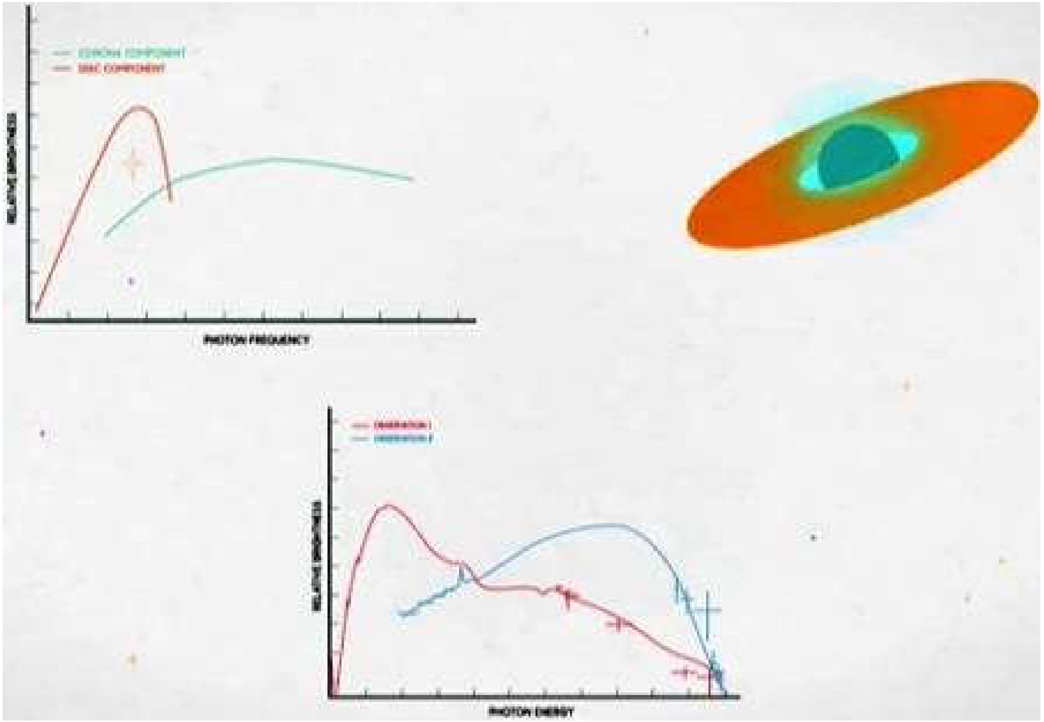
If our portion sizes are changing, how does this affect the view of the system?

Assuming we could go for a visit. Let us simplify things to start off with. We are going to stick with the sandwich model for the rest of this lesson given all of the food.



Here, the filling or a disk takes up a lot of our view. Therefore, we could say it is dominating the illustration. In fact, it is stretching all the way down to the ISCO. This is when the disc is at its brightest. It can be so bright in fact that the emission from the accretion disk can be the brightest component in the optical band of the spectrum. When this is the case, we would not be able to see what kind of star the black hole is consuming. The bread of our sandwich is almost missing. The corona is so thin and wispy that we do not really receive too many photons from it.

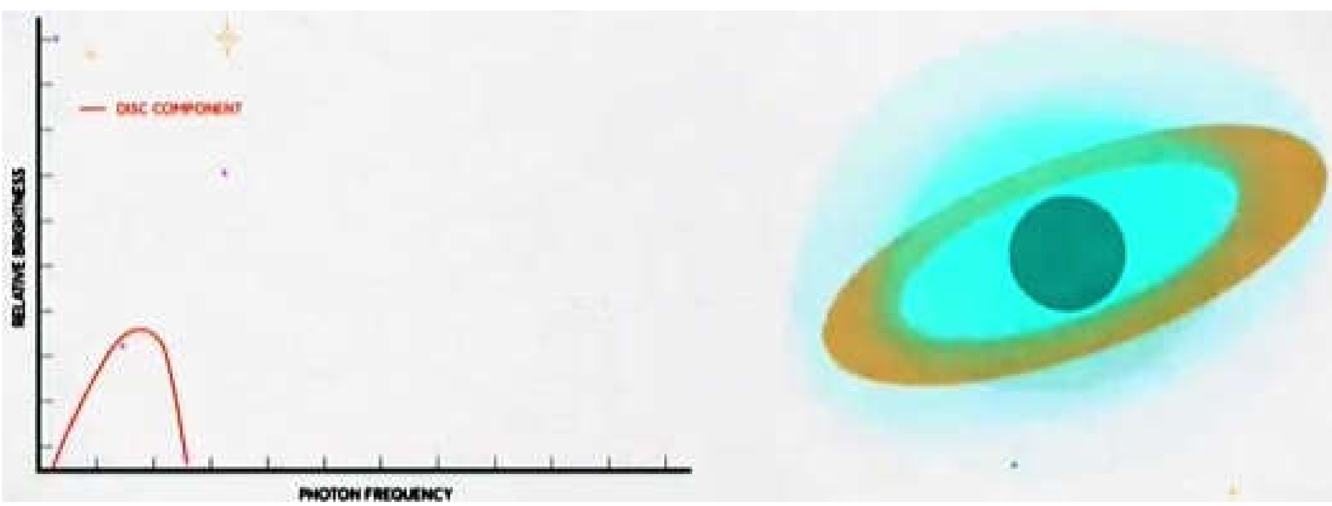
7.1 High State



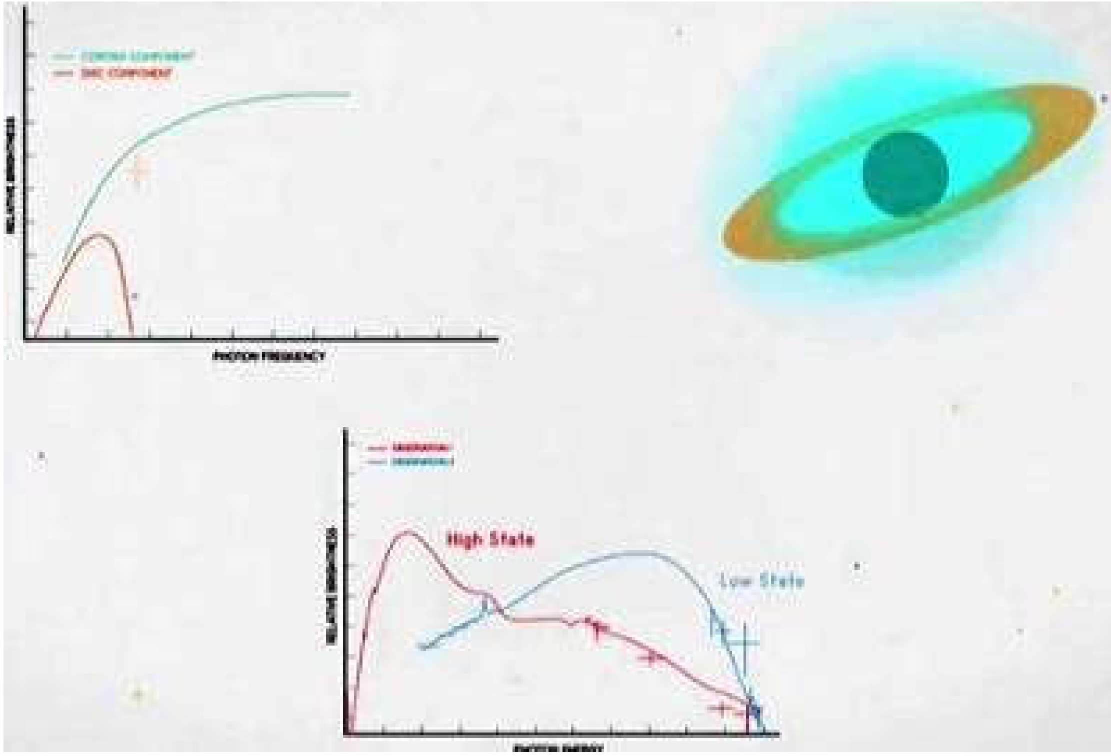
The sketch we see here of our spectrum matches quite closely to the spectrum of Cygnus X-1 shown in red. Astronomers call this the high-state. This name is historical as it comes from the early days of X-ray astronomy. It is known as the high-state, because it is at higher luminosity. It was the brighter option.

7.2 Low-State

Have we mentioned astronomers like simple names?



Following that line of thought, the next state I would like to mention is the low-state, so named because it is the fainter one. When black holes are in the low-state, the sandwich is switched. Where the disk may feel thin, sort of stretched like two little buttons script over too much bread. In the low-state, the innermost part of the disk is not at the ISCO, it is found some distance away. We learned earlier that we could think of the disk as being made up of a series of many rings. As we progress inwards through the disk, the temperature of each ring increases. This means that the highest temperature we detect from the disk, also known as the peak temperature, which come from the innermost ring of the disk. In the low-state, the inner disc is further away from the black hole. This means that the disk spectrum is cooler, and therefore, shifted to the left of our plot. We also find the disc is fainter, so faint in fact that this is a great time to check out the companion stars of the black hole. Here, we have a lot more bread for our sandwich with the corona dominating the innermost region around the black hole. With this increasing corona, we receive more photons as it begins to dominate the X-ray spectrum.

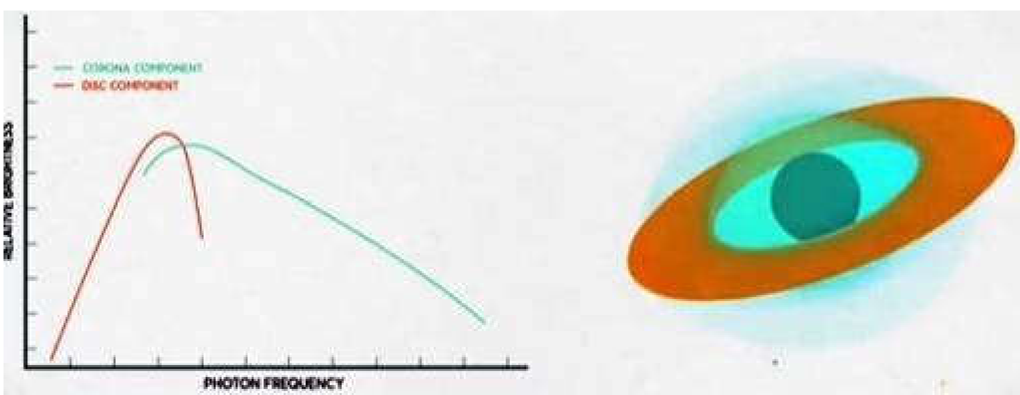


This is more akin to the spectrum of Cygnus X-1 shown here in blue. These two strikingly different views of the same source belt with the same components.

However, what about the jet?

It turns out, although the disc and corona appear to be permanent features, the jet is not. The jet is strongly associated with the low-state. Although astronomers do not fully understand how jets are launched, they have found strong ties between the emission seen in X-rays and the radio emission. By combining information relating to the brightness of these electromagnetic bands, you can obtain estimates on the mass of the central black hole.

7.3 Very High State



In order to investigate the high-state and low-state that had been seen in the emission from stellar-mass black holes in binary systems, astronomers continue to make observations of these sources. Over time, they found that black holes could get even brighter, which seem to correlate with the change in the shape of the spectrum. This called for a new accretion state known as the very high state. If we break this model apart to build an illustration of what we would find there, there are both lots of disc possibly extending to the ISCO, and a lot of corona. In this case, we seem to have a sandwich that is more balanced with both a good amount of filling and bread. During the very high state, it is possible to see the jet. Although it is not always present.

7.4 Intermediate State

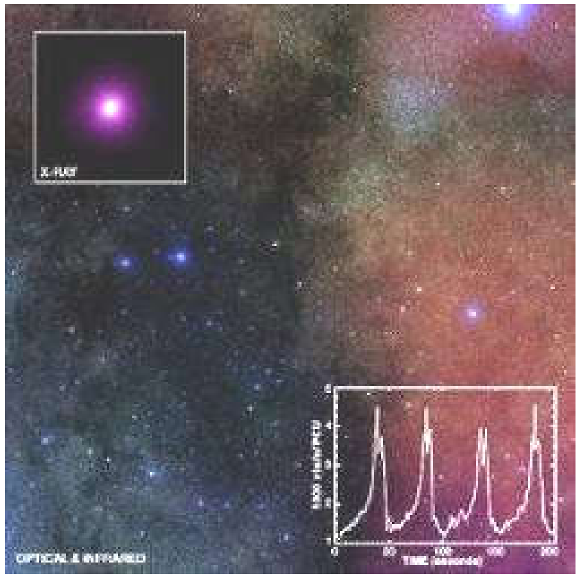
We have explored three black hole brightness states. In addition, some astronomers are lobbying for a fourth intermediate state that seems to live somewhere between the high and low states we have already discussed.

7.5 State-Cycles

How do these states relate to one another?

By looking many times at multiple sources, astronomers have seen cycles emerging within many systems. Cycles start with black holes that are either off or in the low-state. When a feeding frenzy occurs, the black hole will rapidly brighten. This can take as little as hours to occur. Given the rapid rise, many times this can be missed by observers. After the low-state, the black hole transitions to the high-state and possibly even the very high state or beyond. Black holes can hang out in the high-state for a while depending on their food source.

7.6 Outburst



With some sources like GRS 1915+105 seeming to stay in this state for decades. Towards the end of their dinner sitting, they slowly return back to the low-state before feeding away. These cycles are called outbursts. These outbursting cycles can also take place in supermassive black holes, but over much longer time scales, with outbursts lasting centuries, too long for an astronomer to observe in their lifetime.

8 Impact Of Black Holes on Galaxies

Supermassive black holes with masses larger than one million solar masses are found at the centers of most galaxies.

What effect do these black holes have on the galaxies themselves? Do the properties of the host galaxy influence the central black hole?

These questions are important areas of an active study in the field of black hole feedback. A four fold area for black hole physics today.

Let us look again at Sagittarius A*, the black hole at the center of our own galaxy, the Milky Way. Sagittarius A* has a mass of four million times the mass of our Sun. Although this seems impressively large, it is small when compared to the total mass of the entire Milky Way galaxy. Sagittarius A* is $4 * 10^6$ times the mass of our Sun, but the Milky Way is close to 10^{12} solar masses. Therefore, our galaxy is 10^6 times heavier than the black hole at its center. Sagittarius A* contributes only a tiny amount of the total mass of the galaxy.

Similarly, the size of a black hole, Sagittarius A*, is also tiny compared to the size of the galaxy. The radius of Sagittarius A*'s event horizon extends about 12,000,000 km, which itself is almost 30 times larger than the distance between the Moon and the Earth, a reasonable size. However, the event horizon is much smaller than the distance Earth / Sun, which is around 150,000,000 km. Black holes accretion disk is larger, but it is still less than 1 ly across. In contrast, the Milky Way galaxy is huge, with a diameter of more than 100,000 ly. To give you a sense of the astronomical size scale: If Sagittarius A*'s accretion disk will shrink down to the size of a Penny, our galaxy would still be as big as the Earth.

Supermassive black holes living in the centers of other galaxies also have relatively tiny masses and sizes compared to their host galaxies. For instance, the galaxy M87 has a supermassive black hole with a mass of $3 * 10^9$ solar masses. The mass of its host galaxy M87 is > $2 * 10^{12}$ solar masses, which is more than 1,000 times larger than the central black holes mass. This suggests that the overall impact of a supermassive black hole on its host galaxy should be quite small.

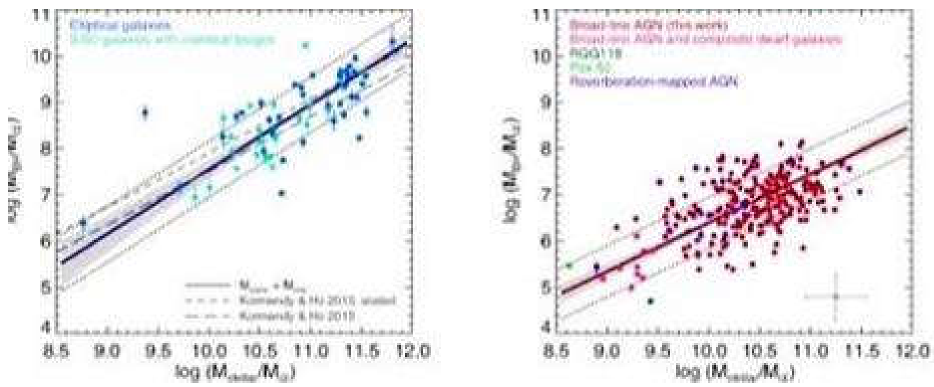


Illustration 128 : Correlation between masses of central black holes and masses of their host galaxies

The funny thing is, this does not seem to be the case. In the 1990s, astronomers measured the masses of many supermassive black holes along with the mass of their host galaxies. They found a strong correlation between the black holes mass and the galaxy's mass. Essentially, they found that larger mass galaxies have larger mass black holes at their centers. They suggests that the galaxies and their central black holes have a symbiotic relationship, meaning that as one grows, so does the other.

This opened up an interesting new area of study that is still under investigation today.

8.1 Feedback

How can they influence each other so much?

The exchange of mass and energy between galaxies and their central black holes is called feedback. The galaxy supplies some gas and dust that accretes onto the central black hole causing the black hole to grow slowly. As the gas accretes, thermal heating causes some of the gas to be ejected from a region near the black hole in the form of high-speed jets. These jets can extend thousands of light-years which heats up the gas and dust in the central parts of the galaxy. Therefore, as long as the galaxy is feeding the black hole, the black hole through some of the gas back out at high-speeds that feeds back into the galaxy.

The outflowing gas can affect the galaxy in two ways:

Firstly, the outflowing gas can push the interstellar gas outwards claiming large regions of gas and dust. By clearing the areas of gas and dust, there is a lack of material required to form new stars. Therefore, this can slow down the birth rate of stars in this region. This may happen in the brightest active galactic nuclei helping regulate star formation.

The second effect of outflowing gas can strangely have the opposite effect. If the black holes jets interact with large gas clouds, they can compress the clouds, triggering formation of new stars. When this happens, the black hole actually helps galaxies form new stars.

The central black hole of a galaxy can suppress or promote the formation of stars that could potentially have planets, and maybe even life. In other words, black holes are not just doom, and gloom, or death through Spaghettification.

8.2 Cosmic Rays

We think of astronomy as a science where cosmic objects, like stars or galaxies, are studied by observing the light that they emit. However, there is more to the Universe than just light. The Universe consists of uncountable elementary particles; like electrons, protons, and neutrons that make up all the elements such as; H, He, a.s.o. These in turn makeup all the molecules and matter. Amazingly here on the Earth, we often detect particles that originate from cosmic sources, particles that come from distant parts of the Universe. These particles are called cosmic rays and carries tremendous amounts of energy.

8.2.1 OMG-Particle

The highest energy cosmic ray ever measured affectionately named the OMG particle carried 48 J of energy. To put that into context, that is about the same as a baseball pitched at a speed of 28 $^{m}/_{s}$. However, since all our energy was carried in atomic nucleus, it was traveling at only a whisper slower than the speed of light.

8.2.2 Cosmic Ray Visual Phenomena

When astronauts travel beyond the protection of Earth's atmosphere, they report strange flashes of light visible even when their eyes are closed. Although this phenomenon has not been studied in detail, scientists think that astronauts are observing flashes of light when a cosmic ray travels through their eyes. These high-energy particles emitted Cherenkov radiation as they pass through. This phenomenon is known as the cosmic ray visual phenomenon.

In order to understand the nature of cosmic rays, which can range from a single electron to nuclei of heavy atoms, we must identify the energy source capable of accelerating them. Lower energy cosmic rays, like the ones we detect from Ozone, are accelerated by the Sun's rapidly changing energetic magnetic fields. High-energy cosmic rays originate outside our solar system and are a common occurrence. They are accelerated during supernova explosions taking place in our own galaxy.

However, where else can they originate?

Most cosmic rays are charged particles like protons or occasionally a heavy atomic nucleus like an atom of Fe. However, we also know about even smaller fundamental particles, like the neutrino. We have already seen that neutrinos, which are uncharged particles with tiny masses, can travel incredible distances without being stopped by interactions with other types of matter. This makes neutrinos almost impossible to detect since it is extremely rare for them to participate in particle interactions. This is why neutrino observatories are some of the most specialized detectors on the planet.

8.3 Neutrino Detectors

Neutrino detectors regularly see neutrinos created in the Sun's core. In 1987 the Kamiokande chain detector in Japan detected neutrinos from a supernova explosion called SN 1987A. This detection led to the award of the Nobel Prize in physics to Masatoshi Koshiba, the leader of the Kamiokande experiment in 2002.

Illustration 129 : Ice cube detector (Antarctica)

More recently, the ice cube detector located in Antarctica detected some very high energy neutrinos that are unlikely to be emitted by supernova. The source of the ice cubes highest-energy neutrinos is still a mystery, but one possibility is that the neutrinos may have come from the jets of a supermassive black hole.

Illustration 130 : Pierre Auger cosmic ray observatory

Occasionally, detectors such as the Pierre Auger cosmic ray observatory in Argentina detect ultra-high energy particles, like the OMG particle. The term ultra-high energy refers to particles whose energies are millions of times more energetic than anything humans can create. What we mean by this is that the highest-energy particles that humans have created are 40 million times less energetic than the highest ultra-high cosmic rays ever seen.

8.3.1 Ultra-High Energy Cosmic Rays

Ultra-high energy cosmic rays cannot originate from supernova explosions. Since scientists have determined through simulations that a supernova cannot accelerate particle to ultra-high energies. The origin of ultra-high energy cosmic rays is still a deep mystery in astrophysics. We do know that the highest-energy cosmic rays almost certainly originate from sources vast distances beyond our galaxy. Again, one plausible explanation is that the jets of supermassive black holes at the centers of distant galaxies are capable of accelerating particles to incredibly high-speeds. If this is true, then our detectors here on the Earth are occasionally registering matter, which escaped from the neighborhood of a black hole.

9 Seeking Out The Elusive

Stellar-mass black-holes have been studied for approximately the last 50 years. Supermassive black holes have been observed for almost as long. However, the identification and study of intermediate-mass black holes is still in it the infancy. The reason for the lack of observations of intermediate-mass black holes is not due to the lack of interest. On the contrary, intermediate-mass black holes are thought to be the seeds of supermassive black holes, and therefore, investigations into their nature could help unlock the mysteries of the formation of supermassive black holes.

The study of intermediate-mass black holes is such a new field, because members of this class of black holes have been incredibly elusive. In the rare instances when intermediate-mass black holes were identified, their classification was contentious, and later many were disproved. At present, there are only a handful of strong candidates for the intermediate-mass black hole class.

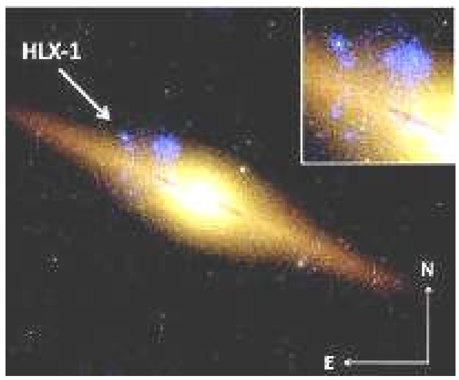
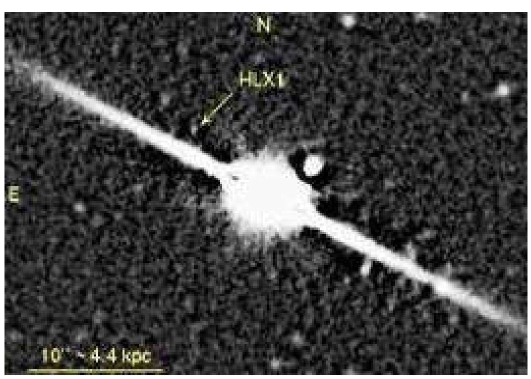


Illustration 131 : ESO243-49HLX-1

ESO243-49HLX-1 is the first candidate of an intermediate-mass black hole we will discuss. This source first hit the headlines in 2009, when its discovery was announced in the journal 'Nature.' This black hole resides in a star cluster that is in orbit around the galaxy ESO243-49, a galaxy that is 320,000,000 ly away from us. The designation HLX means 'hyper luminous X-ray source.' While the one following is the same convention as of our black holes, we have discussed in the course. This is the brightest X-ray object in its host galaxy outside the galaxy's core.

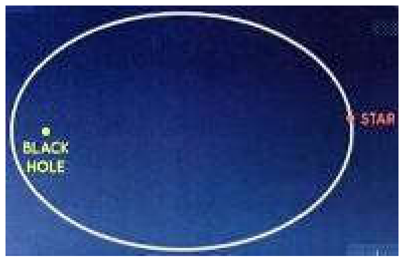


Astronomers were quick to follow up on a source. Making observations in multiple wavelengths from radio, all the way through to X-rays and γ-rays. The temperature of an accretion disc around a black hole can give us an indication of the black holes mass. The more massive the black hole is, the cooler the disc appears to be. We have also found that black holes that are more massive tend to be brighter or more luminous than the lower mass cousins are when they are actively feeding. ESO243-49HLX-1 is approximately 1,000 times brighter than a stellar-mass black hole at the same distance would be.

The main difference observed between ESO243-49HLX-1 and our old friend Cygnus X-1 is that it appears brighter, and its spectrum has been shifted towards the redder end of the spectrum. As astronomers watched over the next few years, we saw repeated brightening of this source. ESO243-49HLX-1 appeared to increase in brightness in a period of just over a year. The spectrum of this source was seen to change in shape with brightness.

The time dependent emission of ESO243-49HLX-1 is very similar to the behavior of X-ray binaries, leading astronomers to believe that it is also a binary system. This means that the black hole, ESO243-49HLX-1, may be actively consuming a star. However, the cyclical nature of the outburst lead some to suggest that this black hole may not be slowly sipping on the surface of a star, but may instead be ripping off larger chunks before gobbling them up in feeding frenzies. This would trigger outbursting behavior observed that mirrors that of outbursts of X-ray binaries.

What could cause these periods of gloat and fasting?



The periodic feeding frenzies could be explained if the binary system's orbit is elliptical instead of circular. This means that the distance between the star and the black hole changes periodically during the orbit. When the star is at its furthest point from the black hole, no mass will be transferred from the star to the black hole. However, when the star is close to the black hole, the gravitational pull of the black hole will increase, allowing the black hole to attract large amounts of material from the star to the accretion disc. This famine and gloat cycle has been suggested as a way to create the regular outburst witnessed from ESO243-49HXL-1.

Further studies have indicated that this black hole weighs in at about 10,000 times the mass of our Sun, and that it resides in the center of a dwarf galaxy that has been stripped and squashed during its interactions with ESO243-49. These interactions may have triggered the formation of the star now feeding the black hole, and may have pushed it into an elliptical orbit that now feeds the beast.

Illustration 132 : Galaxy M82

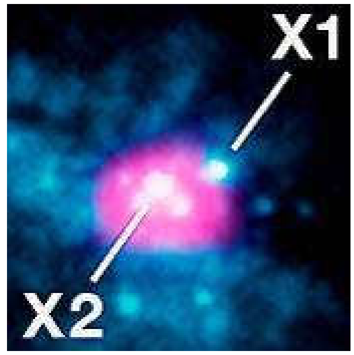
The cigar-shaped galaxy, M82, is the home of another candidate for an intermediate-mass black hole. M82 is a starburst galaxy where stars formed at a rate much higher than in our own galaxy. The X-ray inset shows us a bright X-ray source, named X-1, which is possibly an intermediate-mass black hole.

M82 X-1 lies outside the galaxy's core. It was first detected in 1978 when it picked the interest of astronomers due to its strange brightness. The reason that this source was thought to be so strangely bright, is that it emits light at a much greater rate than we would expect to see if the source was a stellar-mass black hole. The luminosity of M82 X-1 could have been explained by a supermassive black hole, and yet supermassive black holes are found in galaxy centers, while M82 X-1 does not lie in the center of its host galaxy. This left astronomers with two options.

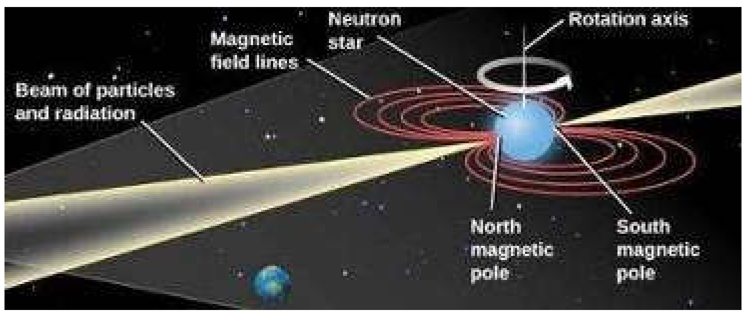
The first option is that this black hole lies in the intermediate-mass black hole range. If this was the case, it could explain the luminosity of M82 X-1.

However, an alternative theory emerged. The idea that this may be a stellar-mass black hole undergoing a feeding frenzy. If it is a stellar-mass black hole, then it is creating a previously unobserved gigantic rate.

As more observations have been made of this source, the mass estimate of M82 X-1 has bounced between stellar-mass and intermediate-mass over the last 40 years. Today, evidence seems to be mounting in support of an intermediate-mass black hole with a mass estimated in the range of 400 – 100,000 solar masses.



It is interesting to note, however, that M82 X-1's close neighbor, M82 X-2, has recently shown just how extreme a creature can get. In 2014, a team working with data from 'New Star', 'CHANDRA', and 'Swift' satellites discovered that a previously observed X-ray source, M82 X-2, is in fact a class of neutron stars known as a pulsar.



A pulsar is a rotating neutron star that shoots jets of emission from its poles. These jets sweep across all field of view as the star rotates like a lighthouse beam, sweeps over the rocks and out to sea. The striking thing about this neutron star is that it is 100 times brighter than theory predicts it could be. This means that M82 X-2 is one of the extreme objects in our galaxy, and it can be used to help us understand how supermassive black holes could grow so quickly in the early Universe.

Enough about neutron stars though. Let us get back to intermediate-mass black holes.

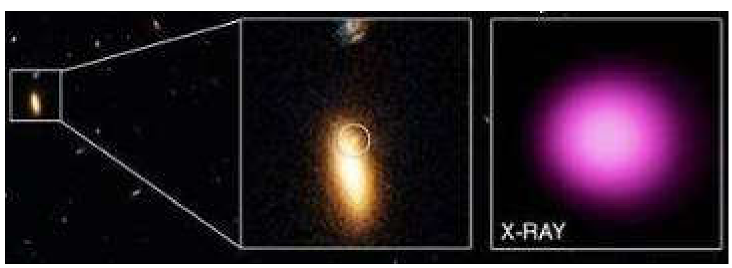


Illustration 133 : XJ1417+52

The next candidate for an intermediate-mass black hole is XJ1417+52. This black hole has a mass that lies at the upper boundary for intermediate-mass black holes approaching the range of the supermassive black holes.

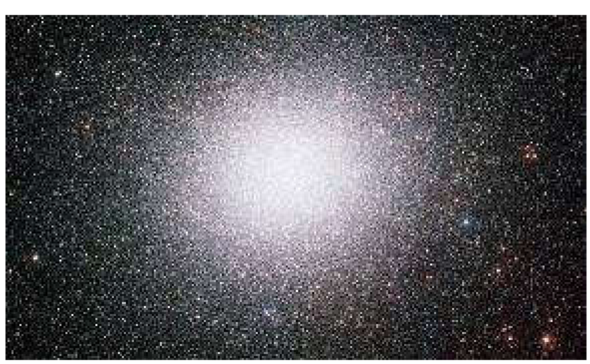


Illustration 134 : Omega Centauri

Omega Centauri is a globular cluster found in the constellation of Centaurus. It is located almost 16,000 ly away, and it is the largest globular cluster in the Milky Way. This star cluster may be home to our final example of a candidate for an intermediate-mass black hole. Unlike the other candidates, this black hole was not identified through its X-ray emission. Most likely, this black hole is not actively feeding since there is no substantial food source nearby. The candidate intermediate-mass black hole in Omega Centauri within feed, I observing the motions of stars using optical telescopes. These stars in the globular cluster move around randomly like a swarm of bees. The speeds of these stars are related to the total mass of the star cluster. From the observations of the star's motion, the mass, the center of the cluster can be inferred. Different observations suggest that a black hole with a mass in the range of 10 - 15,000 solar masses lie in the center of Omega Centauri.

While there are a few other candidate intermediate-mass black holes, their numbers are limited, and many are still contentious. Many candidate intermediate-mass black holes have been ruled out upon further study. The search for the elusive intermediate-mass black hole is an active area of research, a field that is definitely ongoing.

10 Summary

Black holes do not emit light, but that does not mean that we cannot detect them. Just one of the ways is through their interactions with background light: gravitational lensing.

When a black hole is in a binary system, the companion star can be seen. In some cases, mass flows from the companion star into an accretion disk surrounding the black hole, which then emits light. The electromagnetic radiation emitted by the disk, jet, and corona varies in time as the rate of infalling gas changes.

Super-massive black holes, in the center of galaxies, also give away their presence through the energy released by accretion. Jets of gas, energized by gravitational potential energy, interact with the black hole's host galaxy, affecting the formation of nearby stars in the galaxy. Supermassive black hole jets are thought to accelerate particles such as protons and neutrinos. Perhaps this is the origin of cosmic rays.

Isolated black holes most certainly exist in our galaxy, but are hard to detect. They can give away their location when they travel between a distant star and the Earth. The gravitational microlensing effect briefly causes the light from the distant star to appear brighter.

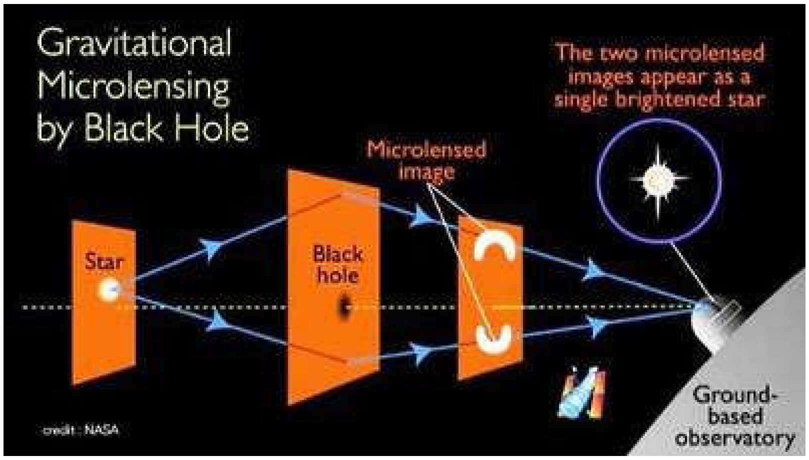
Scientists have learnt all these things through the observation of light or electromagnetic radiation, but this is not the only tool they have at their disposal. Recent projects like ‘LIGO’ and ‘VIRGO’ are built to be incredibly sensitive gravitational wave observatories.

What are they looking for?

They are looking for the evidence of merging black holes, which generate gravitational radiation. That is right, waves in the fabric of space-time.

Gravitational Telescopes

1 Introduction



Our view of black holes has been limited to the electromagnetic radiation that the material falling into the black hole gives off. However, this emitted light will have to travel on curved paths in order to reach our telescopes. As a result, our views of structures near black holes will be warped. New observations by the 'Event Horizon Telescope' will be able to see distortions of space caused by black holes strong gravity.

Visible light is not the only form of electromagnetic radiation. In order to understand black holes, we have had to observe them using X-ray, UV, and radio telescopes. Similarly, electromagnetic radiation is not the only type of radiation.

When masses such as black holes move rapidly, gravitational radiation is emitted. Modern technological advances allow scientists to see with a new kind of eyes. Once they do not see light, but see the stretching and squeezing of space-time itself. By using gravity to probe into the heart of black holes, we can determine details that would otherwise be hidden behind the dust and gas of an accretion disk. Gravitational waves, predicted by Einstein, have recently become the hot new tool to generate scientific data on the behaviors of black holes and compact objects in extreme orbits.

In order to see a gravitational wave, there are a couple options: we can measure the influence of a passing wave on laser beams, or we could precisely time how the pulses of fast rotating pulsars change when a gravitational wave passes by.

Let us start with the simplest way the black hole's gravity effects are observations. Gravitational lensing.

2 Gravitational Lensing

At this point, please watch Astro-101_020.mp4

Video 20 : Gravitational lensing

3 Gravitational Radiation

One of the foundational principles of special relativity is that light always travels at the same constant speed. The speed of light is fast, but it still takes 8.3 minutes to travel the enormous distance from the Sun to the Earth. This means that if the Sun were just suddenly change brightness, there would be a delay of 8.3 minutes before we would see the change here on Earth.

Suppose that powerful aliens with advanced technology managed to change the Sun's gravity, maybe by removing a big blob of hot gas. Removing the gas also causes the Sun to dim at the same time. If we calculate the gravitational traction between the Sun and the Earth, Newton's equations had no time dependents. If the Sun's mass suddenly changes as it were, if aliens removed a large portion of gas, Newton would have predicted that the Earth would feel a different force due to gravity instantaneously, with no delay. If gravity changes instantaneously, as Newton predicted, it would still take the photons admitted by the Sun 8.3 min to reach the Earth, revealing the alien's actions as the Sun becomes dimmer. This means that we could receive information about changes to the Sun at a speed faster than light by using gravity. This instantaneous transmission of information is sometimes called action at a distance.

Einstein realized that Newton's theory of gravity was wrong, because it implies that action at a distance takes place and that gravity could transmit information faster than the speed of light. Although there were no experiments, Einstein could conduct that show that action at a distance is incorrect. Einstein knew that it would imply that there could be ways to transmit information at speeds faster than light, which would contradict the principles of special relativity. Einstein theorized that gravity could be made compatible with special relativity if changes in gravitational fields are transmitted by gravitational waves that obey the speed of light limit in the Universe. Gravitational waves, also called gravitational radiation, are an important part of Einstein's general theory of relativity.

Let us return to the aliens who are changing the Sun's mass and brightness. Einstein's theories predicts that it takes 8.3 minutes for the gravitation force felt by the Earth to change, therefore, changes in gravity travel at the same speed as light. The relationship between the force of gravity and gravitational radiation is similar to the relation between electrostatic forces and the emission of electromagnetic radiation, or light. Electrons, or a proton, are just two examples of charged particles, which create an electrostatic field. Electrostatic fields can be attractive if the force is between opposite charges, or repulsive if the force is between same charges.

By grabbing a balloon against your head, you cause negative charges, or electrons, from your hair to migrate to the balloon, leaving your head with positive charges. If you then hold the negatively charged balloon near your positively charged head, your hairs would stand up, following electrostatic field lines.

The word static means that the system does not change with time. Positive charge, like some hair, will feel an attractive electrostatic force that will feel a force toward the negatively charged balloon. The electric field of the balloon influences nearby objects, but in a static system there is no electromagnetic radiation, or light, emitted in this situation.

If we want to produce electromagnetic radiation, we need to create periodic changes in the static charges. This can be accomplished by changing the position of a charged balloon, say by waving it back and forth rapidly. Positively charged hair will be attracted first in one direction, then the other, a.s.o. This is the situation, which produces a time changing electric and magnetic field that causes a disturbance called electromagnetic radiation; also know as light. For example, if the balloon is moved back and forth once per second, it generates a changing electric field that moves away from the source at the speed of light. One complete cycle of the balloon corresponds to one cycle of the light wave. Therefore, if the balloon moved at 1 Hz, it produces a photon with a wavelength equal to the distance light travels in one second, that is 299,792 km, at the very long end of the wavelength spectrum in the radio frequencies.

This electromagnetic wave travels at the speed of light, perpendicular to the motion that the balloon is being waved. Information about the changing balloons position reaches your hair after time:

$$time = \frac{d}{c}$$

When the wave passes by a charged particle, the particle will feel a time changing force that will cause it to oscillate back and forth in a direction perpendicular to the direction the wave travels in.

Normally, we do not use balloons to create electromagnetic waves. Instead, we might have an alternating current traveling through a dipole antenna to create radio waves, a long wavelength form of light. The important thing to know is that light is only emitted when there are time-changing electric charges, or magnets.

A star or planet has a gravitational field that does not change with time, and unlike electrostatic forces, gravity is only attractive. A small mass placed near a heavy planet will feel an attractive gravitational force that will pull it towards the surface. If there is no motion of the masses, there will be no gravitational radiation emitted. Just like the electrostatic example, in order to excite gravitational waves, we are going to need a gravitational field that changes with time.

3.1 Transverse Waves

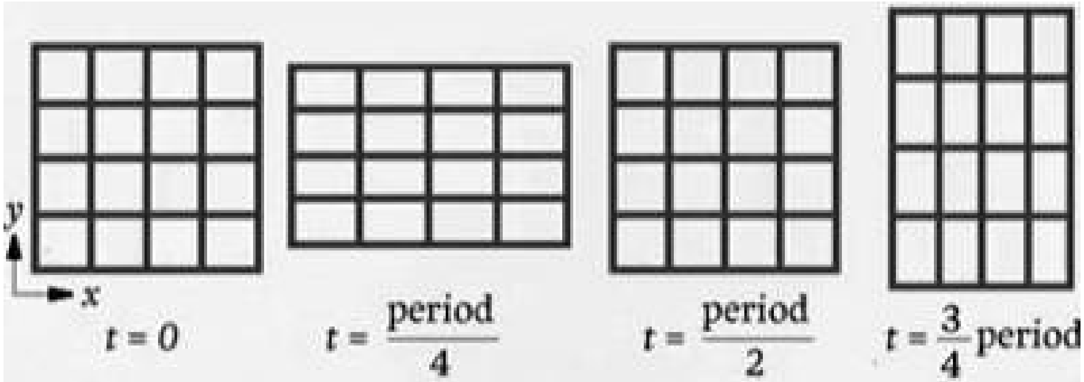


Illustration 135 : Effect of a gravitational wave travelling through the screen

When gravitational waves are created, they move away from their source at the speed of light, and as the wave moves, it distort space-time by stretching and compressing spacial dimensions periodically in the two directions perpendicular to the direction that the wave travels. These waves are called transverse waves and can be understood in a simplified sense. By the analogy of a transverse wave on this rope that Curtis and Ross are playing with.

At this point, please watch Astro-101_021.mp4

Video 21 : Gravitational radiation

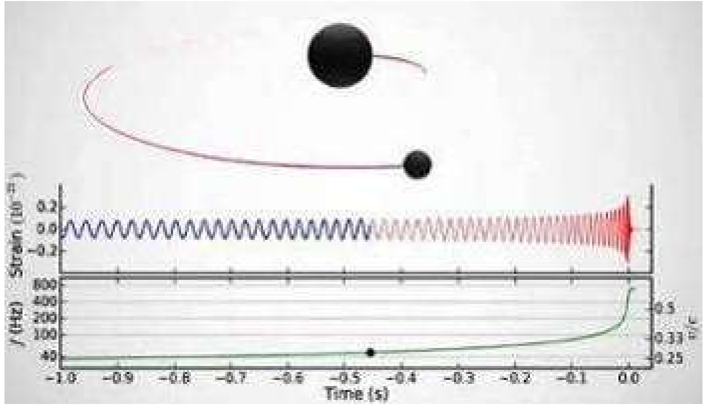
Scientists on Earth have been working hard for decades to build detectors, sensitive enough to detect gravitational waves, and directly detected them for the first time in 2015.

4 Emission Of Gravitational Waves By Binary Systems

Illustration 136 : Gravitational waves from a binary star system

When two stars are in orbit around one another in a binary system, their positions change periodically in time. Since the gravitational force between an astronomer and a star depends on the distance and the direction to the stars, an observer will feel time changing gravitational force, as the two stars orbit one another. As we watch the stars in orbit, we will see the brightness of the system change as they pass in front of one another as they continue their dance through the Universe. To preserve causality, there has to be a delay in the change in the gravitational force that is synchronized with the brightness changes as the locations of the stars change. In other words, the two stars changing positions cause gravitational waves to be emitted by the binary system.

These gravitational waves will distort space-time, and cause objects far away to be squeezed and stretched periodically. The energy for these distortions is carried away from the binary system by a wave. This means that the gravitational waves carry energy away from the binary, and the binary loses orbital energy.



The stars in a binary system are moving in ellipses in accordance with Kepler's laws. One component of the total energy is their kinetic energy, which is kept in balance by their gravitational potential energy. By summing both the kinetic and gravitational potential, we will obtain the total energy for the system. This total energy is large when stars are far away from one another, and smaller when stars are closer to each other. This effect is caused by the emission of gravitational radiation. Outgoing waves carry energy away from the binary causing the stars to fall inwards, orbiting closer and closer to each other, shrinking the orbit of the system, and instead, forming an inward spiral.

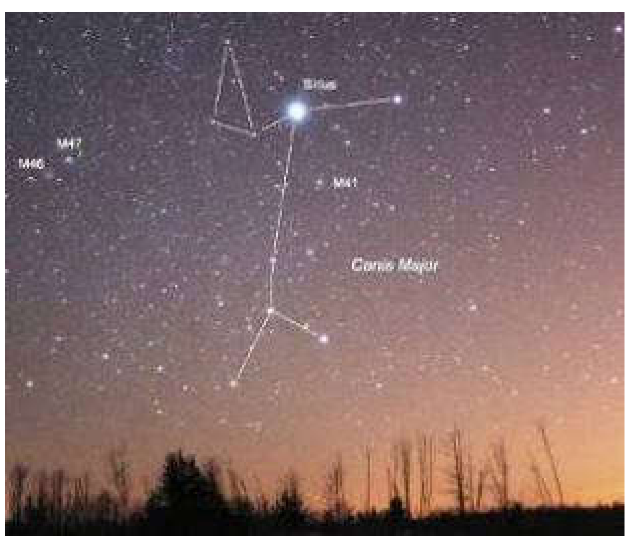
The process of gravitational wave emission and the inward spiral is incredibly slow. Therefore, at any moment in time, we can rearrange Kepler's third law to relate the distance between the stars, *a*, to the time it takes the stars to make one full orbit, *P*.

$$P = \sqrt{\frac{a^3}{M_1 + M_2}}$$

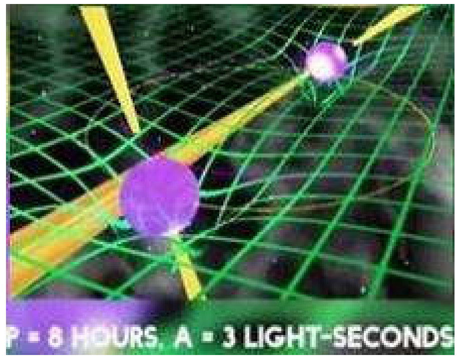
Here we see P, the orbital period. As the stars slowly spiral inward, their masses do not change, only the distance between the stars change. In Kepler's third law, when *a* gets smaller, so does the orbital period, *P*. The star takes less time to orbit when they are close to one another. The result of the loss of energy through gravitational radiation causes binary star systems to slowly spiral inward. As this process continues, the stars' orbits speed up, and they can come closer together, appearing to spin more rapidly around one another. This slow death spiral will eventually cause the two stars to collide, merging into one big star.

This sounds dangerous, and how common would such a phenomenon be?

This death spiral only affects binary stars that are both tiny and extremely close together. In order for two stars in a binary to spiral in and merge within the present age of the Universe, so about 13,000,000,000 years, the distance between the stars has to be no bigger than the diameter of our Sun. That is pretty close. Typical main sequence stars that are found in binary pairs in our galaxy are but much further away from each other than one AU. Moreover, if you recall, one AU is the distance between the Sun and the Earth. Therefore, these typical stellar binaries are in no danger of undergoing inward death spirals.



As an example, the brightest star that we can see in the Earth's night sky is called Sirius, the Dog Star. It is found in the constellation Canis Major, which is named after the mythical dog that got Europa from an abduction by Jupiter. Sirius is actually a binary system composed of two stars that orbit one another every 50 years. The distance between the two stars is similar to the distance between the Sun and the planet Neptune. Gravitational radiation emitted by the Sirius binary system is so weak that currently it is impossible for Earthlings to detect. The in-spiral is so mind bogglingly slow, that it would take 10 zeta years, or 10^{22} years, before the two stars merge. This would be long after both stars burn through their nuclear fuel anyway. In fact, the inspiral of the Sirius binary system takes such a long time that we can ignore the effect of gravitational radiation on this system, and all other binaries of main sequence stars. The only stars that are small enough to allow orbits to be close enough together to emit gravitational waves at observable rates are white dwarfs, neutron stars, and black holes.



The first detected binary star system demonstrating the emission of gravitational waves was a binary composed of two in-spiraling neutron stars. The system was first observed by Russell Hulse and Joseph Taylor, using the Arecibo radio telescope in 1974. It contains a pulsar and a neutron star that orbit one another once every 8 h. Therefore, they are separated by a mere 3 ls, which is similar to the diameter of the Sun.

Together, the two neutron stars slowly spiral in towards each other, allowing Hulse and Taylor to detect the change by measuring the orbital period of the pair over time. They found that the orbit of the two starts slows by approximately $^{1}/_{10}$ ms every year. This tiny change in orbital period agrees with the predictions of gravitational radiation coming from Einstein's theory of general relativity. Although indirect, this was the first evidence of gravitational radiation, demonstrating that gravitational waves do carry energy away from binary systems. This led Hulse and Taylor to be awarded the Nobel Prize in Physics in 1993.

The two neutron stars in the Hulse-Taylor binary system are radiating gravitational waves so slowly, that the stars will not collide for another several billion years. If we want to catch the neutron star collision, direct measurements of the source or the radial telescope just do not cut it. Therefore, in the years since 1974 scientists around the world have been working on the development of sensitive gravitational observatories that allow us to measure the stretch and squeezing of space-time by a gravity wave passing by.

Modern gravitational observatories use lasers to detect gravitational waves. These machines can identify the spiraling of neutron stars at a much later stage. These neutron star binaries have got so close together, that they are able to orbit one another more than 25 times per second. Once a pair of neutron star orbits this quickly, they radiate energetic gravitational waves. The energy of the emitted gravitational waves increases more and more until the two stars spiral close enough that they collide and finally merge. A merger like this can happen in an order of minutes.

Illustration 137 : Hubble image of visible light from the neutron star merger

In August of 2017, such an inspiral of a neutron star binary was detected. In this instance, astronomers also managed to observe the same part of the sky through γ-ray, X-ray, visible light, and radio waves.

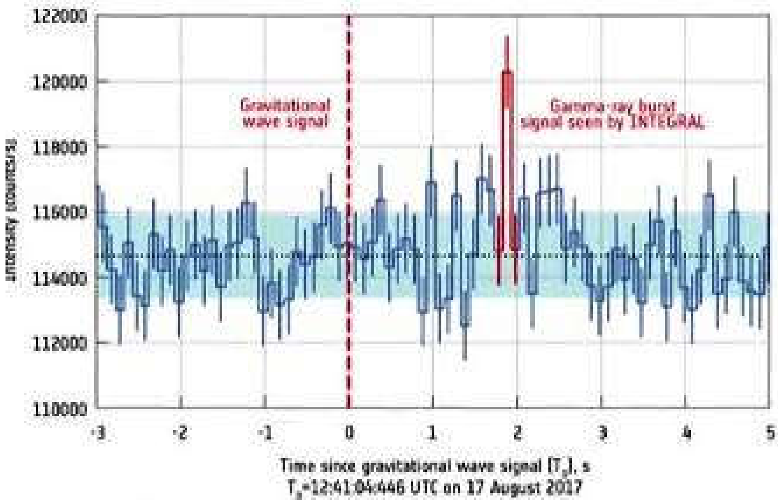
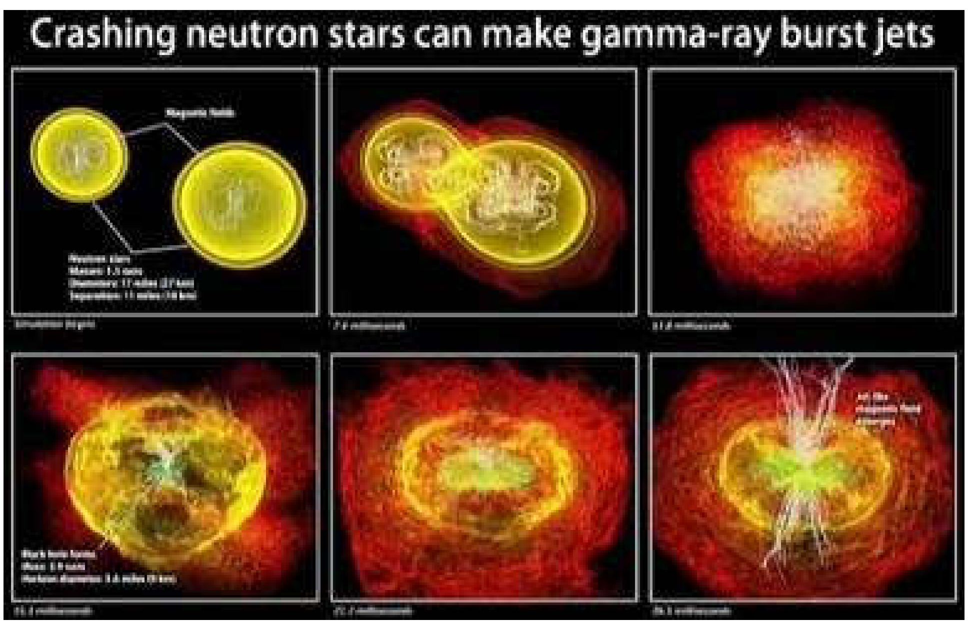


Illustration 138 : γ-ray burst seen soon after the neutron star merger

Several seconds after the gravitational wave observatory detected the merger of the neutron star binary, astronomers saw a bright γ-ray burst in the same direction.

γ-ray bursts come in two types. Short bursts that last for less than a second, and long bursts that last for closer to a minute. Long γ-ray bursts may be associated with collapsars and hyper novae, which might form some black holes. However, in August 2017, the astronomers witnessed a short γ-ray burst right after the merger. This confirmed the suspicion that astronomers had had that short γ-ray bursts are the result of neutron stars smashing into one another.



The smashing together of neutron stars initiates nuclear reactions that allow the formation of elements more massive than those do formed in stars. Those are elements that are heavier than Fe. This includes elements such as Au, Pt, and heavy radioactive elements. Therefore, the next time you wonder where the Au for jewelry comes from, some large fraction of your ring or necklace is the debris of a collision of two neutron stars. These heavy elements can be blown off into space and recycled into the next generation of stars and planets.

However, what is made at the core of this merger?

When two neutron stars merge, there are two possible outcomes for the object left behind. Either the remnant of the merger could be a more massive neutron star, or it could become a newly formed black hole. The outcome of the merger depends on the mass that remains.

Neutron stars have a maximum allowed mass. This maximum mass is not exactly known, but it is somewhere between two and three times the mass of our Sun. Astronomers commonly state that the maximum mass is three solar masses for ease of definition. However, the largest mass is probably a bit smaller than this. If we knew this mass more accurately, this would be helpful when we try to distinguish between neutron stars and black holes.

When the two neutron stars merge, if the total merged mass is smaller than the maximum neutron star mass, then we will end up with a neutron star. Otherwise, if the mass is too high, the neutron star will be unstable, and will collapse to form a black hole.

The collapse of a neutron star into a black hole should also create gravitational waves. These would be more difficult to detect. There was no evidence for waves like these in 2017 neutron star merger. Unfortunately, this means that we just do not know whether the collision resulted in a larger neutron star or a new black hole. This is an example when no detection does answer the question.

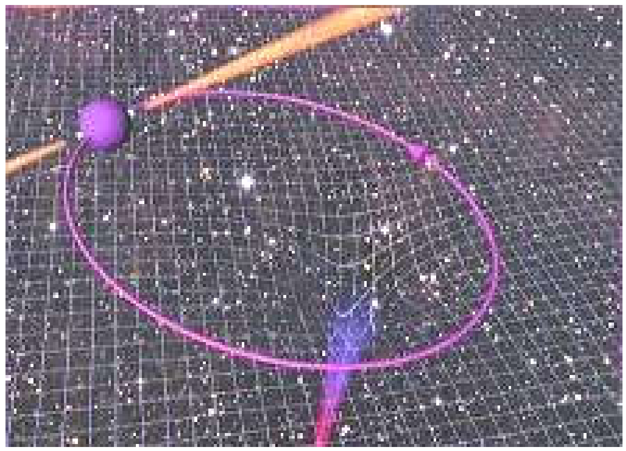


Illustration 139 : Artist's concept of a black hole - neutron star binary system

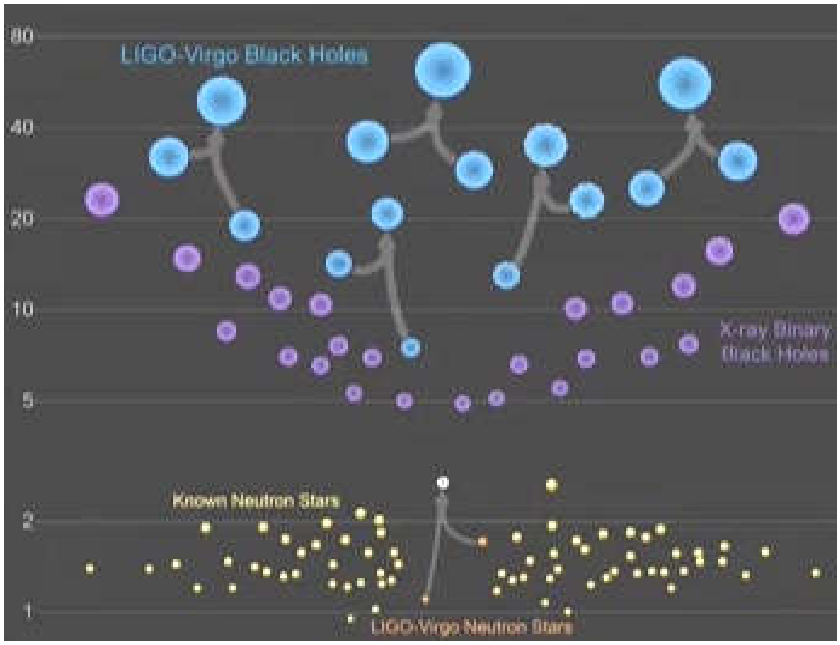
The total mass of the merged objects is 2.7 solar masses, and is very likely that this is larger than the maximum allowed neutron star mass. However, we do not yet have any evidence that tells us that a black hole formed. At present, there has been no observable evidence for a binary system composed of a neutron star and a black hole. However, there is no reason why such a binary should not exist. Assuming that they do exist, there is also no reason why they should not also be able to in-spiral and merge.

Let us imagine what would happen if a black hole merges with a neutron star. Astronomers have tried to model this, and we think it would look very different to that of two neutron stars merging. While the neutron star and the black hole start to in-spiral, it becomes clear that in the end, the neutron star will be ripped apart. It then fall in towards the black hole, and be swallowed by the black hole's event horizon, and the black hole will grow. Although it is quite possible that such a merger would also produce a γ-ray burst, and initiate nuclear reactions that form heavy elements. If a merger of a neutron star and black hole is ever detected, it will be big news, and we will have to update this course.

When a binary system consists of two black holes, they will also in-spiral towards each other due to the emission of gravitational waves, and ultimately merge together. The end state of two black holes merging will be a bigger black hole. As the two black holes merge, for a brief period of time the black hole is a highly distorted mess. However, the no-hair theorem tells us that the normal state for a rotating black hole is a smooth event horizon. During the final merger stage, the distorted black hole emits gravitational radiation in a process called ‘Quasi-Normal Ringdown,’ where all the bumps and wiggles are moved out. The final resulting black hole is a Kerr black hole, of the sort we looked at earlier in the course.

The first black hole merger was detected in 2015, and by the end of 2017, five black hole mergers have been measured. Therefore, by the time you take this course, more of these types of mergers will probably have been detected, and they might eventually seem commonplace.

The data from black hole and neutron star mergers helps astrophysicists understand the distribution of black holes and neutron star sizes in our galaxy, but also the wider Universe. The merger of neutron stars can produce either a new neutron star, or a new black hole. When black holes merge, they become heavier. This diagram summarizes the black hole food chain, as we know it at the end of 2017.



If you look towards the bottom of the diagram, between one and two solar masses, there are collections of yellow circles that represent neutron stars with known masses.

In the middle of all the neutron stars, the two orange balls joined with an arrow that represents the two neutron stars that merged in August 2017. Since there is not enough evidence to determine whether the neutron star became a neutron star or a black hole, the new object is represented with a question mark.

If we move higher up the mass scale, between around 5 and 20 solar masses, there is a collection of purple circles representing known stellar-mass black holes in X-ray binaries.

Finally, at the top of the diagram, there are blue circles, which are joined by arrows that show the merger of lighter black holes, to form heavier black holes. Some of these black hole mergers start off with black holes that are about 30 solar masses, and create black holes that add up to about 60 - 70 solar masses.

This is really exciting, as we can now witness the merger and growth of black holes. Perhaps, this process might lead to the formation of intermediate mass black holes. If we now consider the other end of the black hole mass spectrum, by this I mean, let us switch up to the size of galaxies. Observations of galaxies suggest that almost all galaxies have a supermassive black hole at their center.

Astronomers have been observing galaxies for a long time. While we are used to seeing pretty pictures of spirals and swirls, astronomers have discovered that things can also get a bit messy. This is because galaxies can also collide. When galaxies collide, the black holes can form a binary system, which will emit gravitational waves, in-spiral, and merge. The merger of supermassive black holes has not yet been observed, but they will one day soon.

Ground based gravitational wave observatories are responsible for the direct detection of merging black holes in a stellar-mass range, but feature orbiting space-based gravitational wave detectors are needed before we can detect the merger of supermassive black holes.

We have discussed a lot about the detection of gravitational waves up to this point, but how do these detectors actually measure the effect of a passing gravitational wave?

That is next on our agenda, therefore, let us find out now.

5 Detecting Gravitational Waves With Lasers On Earth

Gravitational waves are extremely weak. These waves would not be felt by a human, for example, or any other living creature for that matter. Therefore, in order to detect gravitational waves, scientists must use the most sensitive instruments ever invented.

What devices are suitable for measuring incredibly small changes?

Well, lasers of course, and that means we will also need our good friend, the Michelson-Morley interferometer. Remember; interferometers leverage the wave nature of light to measure the difference in lengths between different beam paths.

At this point, please watch Astro-101_022.mp4

Video 22 : Basics of a laser-interferometer

Therefore, small changes in the length of one arm of the interferometer can be measured by the changing brightness of the resulting pattern of light at the detector.

The original Michelson-Morley interferometer was developed to determine if the flow of ether caused a delay in one of the device's two arms instead of the difference in the arms' lengths. Like a boat travelling against the current of a river, the theory of light back then predicted that moving ether would cause a delay in the upstream arm. The opposite was discovered; that there was never any delay, no matter what the orientation of the device with respect to the motion through the supposed ether. This proved that light waves do not require a medium like ether to travel in, and as a consequence, the speed of light is a constant.

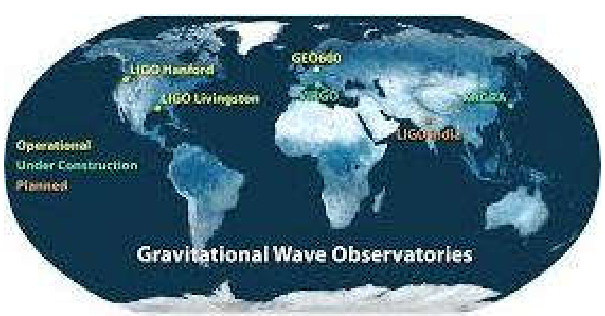
5.1 Gravitational-Wave Observatories

Illustration 140 : LIGO

In order to leverage the sensitivity of interferometers, astronomers built the '**L**aser **I**nterferometer **G**ravitational-wave **O**bservatory,' whose acronym is LIGO. These are two massively improved versions of the Michelson-Morley interferometer built on either side of the continental US. One detector is in Hanford, Washington, while the other is precisely 3,002 km away in Livingston, Louisiana. They each have two arms, but instead of short meter long arms, like the original Michelson-Morley interferometer, each of the arms of LIGO is 4 km long. In addition to the length, each arm bounces light from the laser source back and forth about 280 times making each arm of LIGO equivalent to the length of 1,120 km.

Why are LIGO's arms so long?

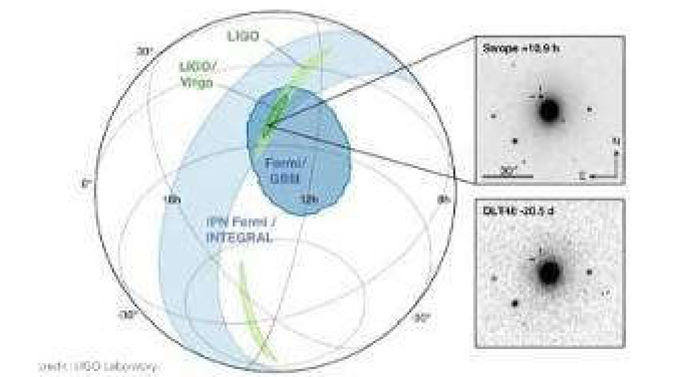
Well, it is hunting for some of the weakest signals that the Universe has ever thrown at us. In fact, in order for LIGO to detect the strongest gravitational waves, it needs to be able to distinguish a change over the 4 km length of its detector arms, a difference in length 1,000 times smaller than the radius of a proton. However, one LIGO is not enough to catch a gravitational wave; we need at least two.



There are several major gravitational-wave observatories in operation around the world. The two LIGO-observatories were the first, followed by Virgo, and a host of others in operation and under construction around the world.

If one LIGO-detector is sensitive enough to measure a change in its arm length down to the level below the width of an atom, why make more?

The first and most important reason is noise. Yes, sounds, footsteps, earthquakes, and cosmic gravity quakes, all register in LIGO as a change in the length of LIGO's arms. In order to filter out footsteps from a colliding black hole, you need a second detector. LIGO second detector, built in Livingston, Louisiana, has a different set of sounds, footsteps, and earthquakes. However, presumably, the two LIGO detectors would both see the same gravitational wave coming from an intergalactic source. To determine whether a wiggle in one LIGO detector is the result of a gravitational wave, scientists compare the data from the second. If there is a wiggle at nearly the same time, remember the detectors are separated by 3,002 km, with nearly the same shape, scientists can be confident that they really saw a gravitational wave, and not some researcher sneezing in the control room.



Nevertheless, there is another important reason to have more than one gravitational observatory, direction. With only two LIGO-detectors, an incoming gravitational wave will not have a well-defined direction. Just as having two ears gives a stereo hearing, two LIGOs let us determine approximately, where the sources are. Although with only two, there is still uncertainty about which direction it came from. In order to pin down the source of gravitational waves, a third gravitational-observatory is necessary. In the case of the kilonova explosion resulting from the merger of two neutron stars in 2017, the gravitational wave signal was also detected by a third gravitational wave observatory, Virgo, in Italy.

With all three gravity wave observatories up and running, most major astrophysical merges will be detected. Over the next few decades, these types of observatories will get more and more sophisticated, detecting dozens of compact object collisions in the Universe. However, things will get really interesting once we send these massive observatories into space.

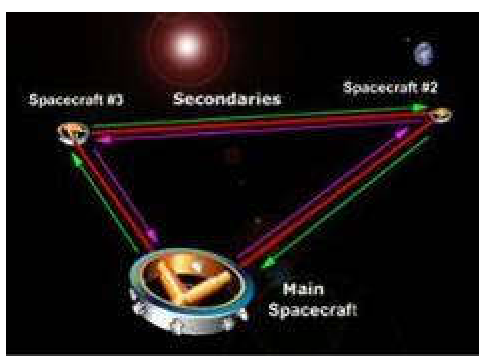


Illustration 141 : LISA

In order to make the most sensitive gravitational wave observatories, scientists work hard to remove sources of error. Just like telescopes, which are better if they are on mountaintops, but best if they are in space, a space-based gravitational-observatory would not have to worry about earthquakes or someone tripping on a banana peel near the detector. Know the next generation of gravitational-observatories will be built in space, the '**L**aser **I**nterferometer **S**pace **O**bservatory,' whose acronym is LISA. LISA consists of three spacecraft, which will trail behind Earth in its orbit around the Sun, flying in a triangular formation. Each of LISA's arms extends between the three spacecrafts. Instead of a puny 1,120 km effective arm length, LISA will have three 2,500,000 km long arms.

LISA will still be sensitive to small changes in the length between the arms, but we will have an incredible sensitivity of 20 pm over the 2,500,000 km long arms. As a result, LISA will be able to detect much smaller and quieter collisions than LIGO, but also begin probing into the processes by which compact objects are captured by, but not collided with black holes. Beyond LISA, which will not even launch until the early 2030's, future gravitational observatories will measure the rotation of compact objects like pulsars.

6 Pulsar Positioning System

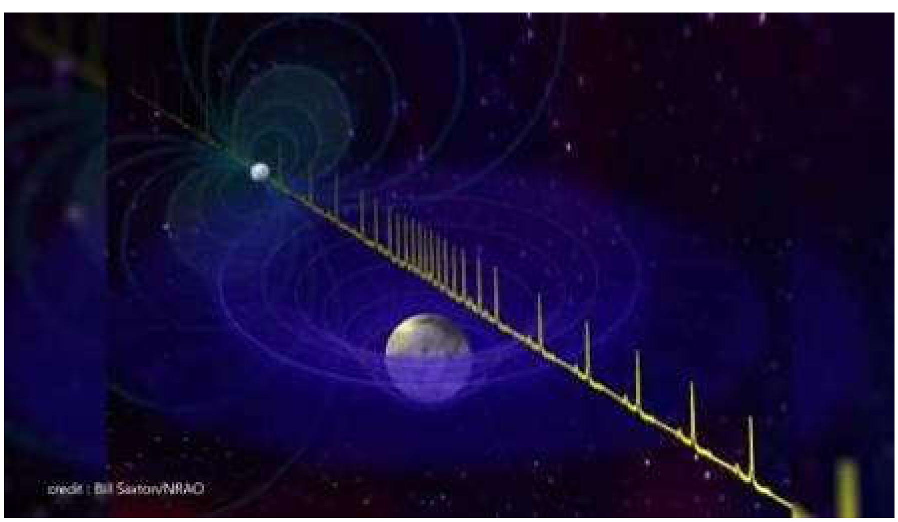
Since existing gravitational observatories can only detect the strongest waves created in collisions of massive black holes and neutron stars, future detectors are being made with ever-increasing sensitivities to find more subtle changes in the fabric of space-time. One concept being developed is called a '**P**ulsar-**T**iming **A**rray,' which would allow scientists to probe Einstein's general theory of relativity and the effects of gravitational waves over thousands of light-years.

credit : NASA's Goddard Space Flight Center Conceptual Image Lab

Since a pulsar is a rotating neutron star, which emits a jet of radiation. If the beam of the jet points towards Earth, we detect a short radio burst. Those radio bursts arrive at regular intervals, sweeping across the Earth for every rotation of the pulsar.

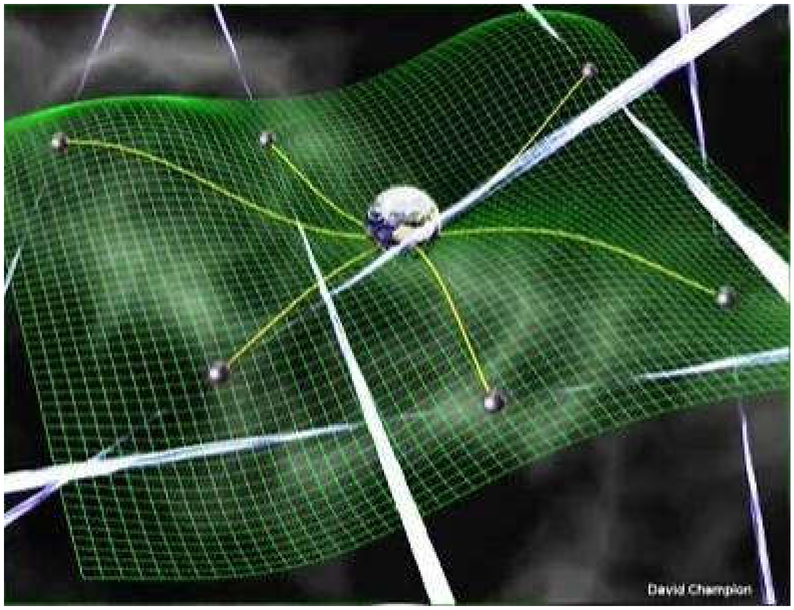
The fastest spinning pulsar, PSR J1748-2446AD, which lives within the globular cluster of Terzan 5, 18.800 ly from Earth, rotates 716 $^{1}/_{s}$, which would sound like an F5 tone if the radio pulses were converted to sound.

A spinning pulsar is of great interest, because some pulsar's rotation rates are incredibly stable, so that they can arrival the precision of atomic clocks. PSR J1748, the fastest spinning pulsar has been measured to rotate exactly once every 0.01395952482 s, with an error of less than 600 fs. This incredibly precise timing is one of the most accurately measured observables in all of astrophysics. By the way, this pulsar was discovered by Dr. Jason Hustle, who graduated with a Bachelor of Science in Honors Physics from the 'University of Alberta.'



credit : Bill Saxton/NRAO

The precision of a pulsars rotation rate is very much like a clock ticking at regular intervals. Just like the effects of gravitational Doppler shift that redshift photons as they escape from a gravity well, gravitational waves alter the timing of pulses from pulsars.



In order to do actually anything useful though, you need several pulsars in an array. Now, you know why they are called pulsar-timing arrays. It may be easier to imagine pulsar-timing arrays as similar to the technology that underpins the GPS. The GPS-sensors in Smartphone’s and navigation devices work by listening carefully for radio signals from GPS-satellites high in orbit above Earth. By comparing the arrival time of the pulses from each GPS-satellite, your device can triangulate your position on the surface of the Earth.

NASA's Nicer-sextant X-ray telescope, which is on the ISS, is observing a collection of X-ray pulsars to test out the feasibility of using pulsar arrays as future navigational aids. By listening to the regular pulses from several nearby pulsars, you could triangulate your position anywhere in interstellar space around those pulsars.

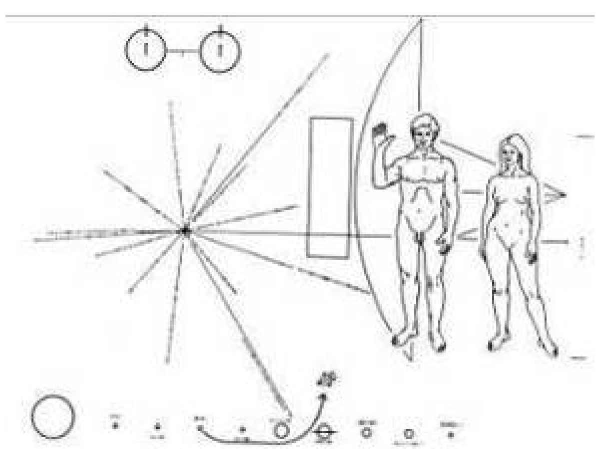


Illustration 142 : Map mounted on Pioneer 10

This map, created by the JPL, was affixed to the Pioneer 10 spacecraft, which after completing a survey of Jupiter became the first satellite with sufficient escape velocity to leave the solar system. The image shows the relative positions of pulsars near Earth with their particular timings encoded on the line that joins them. If this map were discovered, the position of Earth could be deduced. However, our civilization has not reached the point of navigating with pulsar-timing arrays. Instead, we are patiently listening to them for evidence of large-scale gravitational waves passing in between Earth and the pulsars.

When a gravitational wave passes in between the Earth and a pulsar, it causes a distortion of space-time that affects how signals propagate. Generally speaking, the signals from pulsars will appear either delayed or accelerated due to the influence of a passing gravitational wave. Just as a black hole creates a gravitational potential well and the associated effects of gravitational redshift and time dilation, so too can a gravitational wave create immeasurable effects as it passes by. Imagine for example that you usually drive to work or school on a flat road. The time it takes you to get from point A to point B along your route takes about the same amount of time.

What would happen if all of a sudden along the route, a hill appeared? Alternatively, what if a depression appeared in the road instead?

In both cases, the time it takes you to go from A to B will change ever so slightly depending on the size of the hill. A gravitational wave in space-time is just like this hill. Only since it is a wave, it will be a moving hill. If the timing of a gravitational wave is just right, it compresses the space-time that the pulsar signals are travelling through offsetting the arrival time by a small difference, which is called the timing residual. The timing residual is a measurement of the difference between the expected arrival time of the signal and the observed arrival time. Since gravitational waves can both stretch and squeeze space-time, whether the signal is delayed or accelerated will depend on the geometry of the pulsar-timing array and the incident gravitational waves.

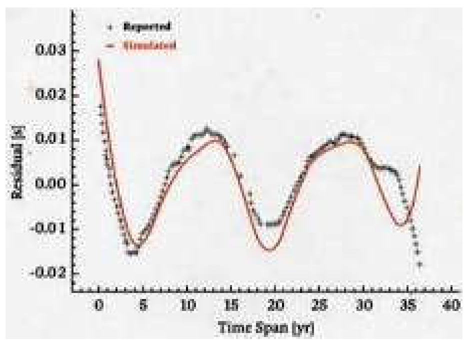


Illustration 143 : Timing residuals of pulsar spins

So far, this method of monitoring pulsar-timing arrays has not resulted in any observations of gravitational waves. However, techniques like these are a complement to the interferometer based gravitational observatories, and will eventually contribute to the detection of more massive binary collisions.

7 Course Wrap-Up!

Black holes on the media are portrayed as matter-thirsty objects with infinite hunger. They tear astronauts apart, cause incalculable damage, and facilitate impossible feats of time travel. These often-misunderstood objects have been discovered and studied only over the last half century. Black holes reveal to us the depth and breadth of the known Universe, and the tremendous success of general relativity, but they do hide their dark sides.

As the brightest objects in the Universe, quasars and blazars are powered by supermassive black holes accreting material onto accretion disks. Recent black hole mergers observed by LEGO reveal just how many black holes are out there, and observations from the Event Horizon Telescope give us our first glimpse at Sagittarius A*, our galaxy's very own supermassive black hole. However, physicists are well aware that we have much more to learn about black holes, and to pass that knowledge on to artists and filmmakers who have a passion for science.

In this course, we learned that a black hole forms, if we can find a way to squash the mass of an object down into a small volume with a radius less than or equal to the Schwarzschild radius. It is difficult to make a black hole since this matter is squeezed into smaller volumes, other forces will tend to oppose this motion and push outwards. For instance, nuclear reactions in the core of the star heat up the star and provide an outward gas pressure that balances gravity. As a result, we have stars that can live long stable lives for billions of years, potentially providing heat to life on orbiting planets. Black holes can form when very high mass stars cannot provide enough heat from nuclear reactions, to provide the gas pressure and keep up hydrostatic equilibrium. The laws of nuclear fuel leads to the implosion of the star that can, in some cases, create a black hole.

Another way to create a black hole is to smash two neutron stars together. If the resulting mass of material is high enough it can collapse into a black hole. I do not know about you, but I am feeling overwhelmed by all the information I learned from the course. I really want to go back now to the scenes in Star Trek that we discussed at the beginning of the course, to compare what we saw then to what we know now.

As you probably recall, in 2009 Star Trek movie "Reboot," red matter is employed as a quick method of creating a black hole. While there is still no scientific basis for red matter or even the creation of a black hole through current human technologies, the destruction of the planet Vulcan due to a black hole is still a frightening thought. We now know that even if it were possible to create a black hole say in a particle accelerator like the Large Hadron Collider, the black hole would be tiny. It will be so small that its temperature would be millions of times hotter than the Sun, and quantum effects would quickly work on evaporating the black hole through Hawking radiation. If the mass of the red matter black hole were similar to the mass of a proton, then the Hawking radiation would make black hole unstable, and it would disappear in a tiny fraction of a second after it was formed. This might create a small burst of energy, but not nearly enough to destroy a planet.

That is not where the scientific inaccuracy stops either. Let us say that red matter did create a miniature black hole that caused the collapse of the planet surface, the planet would not vanish as it did in the movie, and instead the infalling matter would accrete around the black hole, heating up to thousands and millions of degrees. Instead of watching the collapse, you would see instead blinding X-ray radiation, literally blinding if you happen to be close. Although scientists have never observed such low mass black holes, it is likely that all models applied to accretion disks, larger black holes would scale appropriately.

I do not bring up these issues, because the scientific inaccuracies make 'Star Trek' a poor movie, quite the opposite in fact. Without shortcuts around some of the difficult scientific principles, 'Star Trek' would just be another documentary about black holes. Nevertheless, when scientific principles are applied correctly, as they were in 'Interstellar', the whole story gains a renewed significance. Where 'Star Trek' lives in the realm of SF, we can envision ourselves in a scientifically accurate future like the one 'Interstellar' portrays.

We can often find shortcuts taken by filmmakers and artists while portraying the astonishing environments around black holes, but the reality of black holes is much stranger than anything that has yet been captured on film. Science fact as it were still beats science fiction for the strangeness of black holes. Einstein's insights into the structure of space-time, insights that required a powerful imagination along with an app for mathematics, were a giant leap from the Newtonian framework of gravitation. As a result, we know that in our Universe there is a trade-off between how quickly you can travel, and how quickly the clocks in your reference frame tick. Even thinking about that is giving me a bit of a brain cramp.

Imagining space-time is nothing compared to speculating about the interior of black holes. In both Disney's 'The Black Hole' and Christopher Nolan's 'Interstellar', characters are portrayed as crossing the event horizon. As astounding as the effects may be, the events portrayed in these movies taking place within the event horizon of a black hole is pure speculation. Physicists make use of Penrose diagrams to try to explain the interior of black holes.

Modern theories predict that anything that enters into a black hole will have to collide with the singularity, which is likely fatal. We talked about the escape from a black hole as impossible, but we also know that the process of Hawking radiation allows the escape of particles from a black hole when pairs of particles and anti-particles are created near the event horizon.

Which is it? Can particles escape from black holes, but not something big like me? As quantum physicists are keen on saying, information cannot be destroyed, what happens when I drop a memory device into the black hole? Can I read that information out of the Hawking radiation at a later time? Does the black hole somehow encode everything falling into it as the Universe's most compact hard-drive?

The idea of a black hole has been around for a long time and, more recently, a key component of many science fiction tales. Optical observations of black hole binaries have allowed us to look at the companions to black holes, watching them move in orbit around the binaries common center of mass. Using this information, we have been able to find out more about the types of stars that hang out with black holes. We have been able to learn about how they can transfer material to the black hole, and how black holes can get their food.

X-ray and radio observations of black hole binaries have given us the opportunity to learn more about what is going on close to the black hole by giving us an insight into accretion processes. These views allow us to test theories about the physics of matter in the presence of extreme gravity. While we are currently unable to visit the black hole ourselves, observations of them have taught us much more about the Universe. The closest known black hole to us is V616 Monocerotis. It lives about 3,500 ly away from us. V616 Mon is a black hole that lives in a binary system with an orange companion star. The black hole weighs in at about seven solar masses.

The furthest known black hole, ULAS J1342+0928 was discovered in 2017. This supermassive black hole has a mass of 800,000,000 solar masses. Its light has taken 13.1 billion years to get to us, and it was emitted only 619,000,000 years after the Big Bang. The discovery of distant black holes allows us to learn more about the early Universe, the formation of the first supermassive black holes, and the formation of galaxies.

The smallest known black hole, XTE J1650-500, has a mass that is approximately five times the mass of our Sun. This means that the event horizon radius is only 15 km. The largest known black hole is S5 0014+81, an optically violent variable quasar. This black holes mass is 40,000,000,000 solar masses, and it is also one of the most luminous black holes, emitting radiation equivalent to 10^{14} suns.

The faintest black hole is something harder to determine. One contender is that is Swift J1357.2-0933, a stellar mass black hole in a binary system, located only 4,900 ly away. Moreover, it emits light that is only 100 times brighter than the Sun in the X-ray band.

While black holes appear to be mysterious, we have learned that the basic ideas and observations can be described using known scientific principles. Astrophysicists are well aware that a theory of quantum gravity is required to explain quantum phenomena associated with black holes on tiny scales. However, there are much more unknown unknowns that we can only just begin pondering about, like the nature of gravitational waves. The observations of gravitational radiation from merging black holes and neutron stars have opened up a new way to learn about black holes. We cannot know what will be discovered, but we can guess some possibilities. I am hoping we will observe gravitational waves from merging supermassive black holes at the centers of galaxies. Maybe we will get to see the first evidence for a binary system composed of a neutron star and a black hole, giving off gravitational waves as they merge. It may also be possible to see gravitational waves when stars are tidally disrupted by black holes.

Appendix

1 List of Equations

2 List of Formulas

3 List of Illustrations

4 List of Tables

5 List of Videos